Evaluation and Analysis of NAEMS Layer Data

Final Report

Submitted to

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Table of Contents

List of Figures

List of Tables

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1. INDUSTRY SUMMARY

1.1. Executive Abstract

An agreement between the U.S. EPA and four major livestock and poultry groups called the Air Consent Agreement (ACA) included provisions for the participating industries to provide funding for the National Air Emissions Monitoring Study (NAEMS). In the case of the egg industry, the NAEMS was a two-year quality-assured field measurement of ammonia (NH_3), hydrogen sulfide (H_2S), particulate matter (PM) and volatile organic compounds (VOC) emissions from a total of eight layer houses and a manure shed. At each field monitoring site, an on-farm instrumentation shelter housed instruments for continuously measuring pollutant concentrations, house ventilation rates, and environmental variables. Data logged every 60 s between 2007 and 2009 using harmonized protocols among farms was processed and delivered to the U.S. EPA in 2010. Later this year, the EPA will begin using the hourly and daily means of the emission data to develop estimating methods that are expected to be announced after their analysis is complete and reviewed by NAEMS CAFO the EPA's Science Advisory Panel and commented on by the livestock and poultry community and the general public.

The quality-assured data showed that egg laying farms, as they are currently operated, emit less than the 100 lb/day reporting threshold for H_2S and the annual 250 tons per year threshold for PM_{10}. The TSP emissions were greater than the PM_{10} emissions but TSP emissions are not regulated. The $PM_{2.5}$ emissions were only a small fraction of the PM_{10} emissions.

Conversely, the NH_3 data showed that egg laying farms, as they are operated today, will emit more NH_3 than the reporting threshold. These data indicate that producers can multiply simple emissions factors times their number of laying hens to obtain accurate estimates of the amount of ammonia emitted from their facilities. For example, producers can multiply their inventories by 0.0019359 lb/d-hen (0.88 g/d-hen) for high rise houses and by 0.00063877 lb/d-hen (0.29 g/d-hen) for belt houses. For example, the estimate for a 2.5 million hen manure belt facility, the reported emissions would be 2,500,000 hens x 0.00063877 lb/d-hen = 1,600 lb/d, and classified as a continuous release.

While the Clean Air Act has an annual threshold VOC emission of 250 tons per year, VOCs are very complex, and difficult and expensive to measure. It is therefore not surprising that no VOC emission factors yet exist for livestock facilities at the federal level. The limited VOC dataset obtained by the NAEMS showed that the annualized emissions from high rise and manure belt facilities had similar VOC emission rates and that 11.6 million hens were required to emit 250 tons per year and 4.6 million to exceed 100 tons per year.

1.2. Introduction

In the late 1990s the US EPA began to explore regulating air emissions from livestock and poultry farms. EPA lacked clear science about the precise nature and quantity of these emissions, and it had not issued any regulatory guidance to producers about how the air quality laws might apply to them. The data on ammonia (NH_3), hydrogen sulfide (H_2S), volatile organic compounds

(VOC), and particulate matter (PM) was either too scarce to provide sufficient knowledge about the quantity of emissions or existing data was not collected under sufficient quality control to assure its reliability (National Research Council, 2003). Recognizing this, EPA and members of the livestock poultry community entered into negotiations in 2003 to develop an Air Consent Agreement to facilitate the conduct of the scientific inquiry and the development of the guidance that was needed.

Egg producers across the nation voluntarily signed up in 2005 to participate in the Air Consent Agreement (ACA), a short name for the Air Emissions Consent Agreement and Final Order, which was announced by the U.S. EPA (Environmental Protection Agency) in January of 2005. In the ACA, EPA pledged not to litigate against participating livestock and poultry farms for alleged past violations of air emissions laws or for such violations during the period of the industry funded field studies to monitor the regulated pollutants including PM (TSP, PM_{10} and $PM_{2.5}$), H_2S, VOC, and NH_3 from commercial farms, as well as during the period following the study while EPA generates emissions estimation methodologies.

The EPA's goal of the National Air Emissions Monitoring Study (NA collected data to estimate regulated emissions for all layer operations using science-based methods. The term used in the ACA for these science-based methods are "emission estimation methodologies" (EEMs), but the end result could range from a one-size-fits-all emissions factor to a sophisticated computer model that inputs various things about the farm. EPA's final layer EEMs, when issued, will be the accepted standard for determining the amount of air emissions from layer operations that could be subject to the applicable regulatory requirements.

The livestock and poultry organizations representing producers that are participating in the ACA formed the Agricultural Air Research Council (AARC) in 2006. The AARC submitted to the EPA their selections of three representative egg farms from among the facilities of the 204 ACA participants who raise egg laying hens. The selected layer operations were located in California, Indiana, and North Carolina and the emissions from their facilities were unmitigated. The study to quantify pollutant emissions from egg and other facilities was laun of the farm selection and the detailed test methods and farm-specific monitoring plans in late 2006. The two-year study was conducted from 2007 to 2009. At each site, layer house emissions were monitored, and pertinent farm data such as feed information, egg production, manure characteristics, and flock data were collected. A total of over 700 million data points were collected from the three farms to provide reliable data for developing and validating emissions models and for use as the applicable estimates of emissions potential subject to regulations.

Purdue University led the overall study with scientists and engineers from Purdue University, North Carolina State University and the University of California - Davis responsible for the work at each site. Purdue submitted four separate egg research reports containing all data collected from each site to EPA in July, 2010. On Jan. 13, 2011, EPA made the reports publically available at www.epa.gov/airquality/agmonitoring/index.html. When the EPA completes their review of the data, they will announce the posting of the EEMs on the EPA web site in the Federal Register (www.gpoaccess.gov/index.html). ACA participants will have 60 d after the release of the EEMs to certify in writing that their emissions do not subject them to the applicable regulatory requirements, if any. If they cannot certify this, then the producers have 120 d to comply with the applicable regulatory requirements.

1.3. Objectives and Approach

The primary objective of the NAEMS was to reliably quantify emissions of $PM_{2.5}$, PM_{10}, TSP, NH_3, H_2S, and non-methane volatile organic compounds (NMVOC) from facilities of participating farms for validating models and comparing with regulatory thresholds. Federal and state regulators will use the data to determine new emission factors and models for use in enforcement actions related to the CAA and EPCRA. If possible, the industries will use the data in considering mitigation approaches for complying with regulations. Finally, academic researchers will use the data to validate scientific emissions models (Heber et al., 2011).

The NAEMS was conducted at the three selected layer farms for a period of two (2) years starting in 2007. Two high-rise houses were monitored at the farms in California (CA2B) and North Carolina (NC2B). The Indiana farm actually consisted of two independent monitoring sites, one at two high-rise houses (IN2H) and one at two manure belt houses and a manure shed (IN2B), so there was a total of four monitoring sites at three farms, including six high-rise houses and two belt houses (Table 1-11.1). All houses were mechanically-ventilated and the manure shed for the manure belt houses was naturally ventilated (Heber et al., 2008).

Table 1-1. Description of monitored buildings at layer farms.

Site	Type (date)	Qty.	Capacity	# fans/house	# sensors	GSL	PML
CA2B	High-rise, DB	2	38,000	12	104	7	3
NC2B	High-rise, CBC	2	103,000	34	140	7	3
IN2H	High-rise, CBC	2	250,000	110	169	15	3
IN2B	Manure belt (	2	280,000	96	297	18	5
IN2B	Manure shed (	1	-	0		1	1

DB = cages with dropping boards; CBC = curtain backed cages; GSL = gas sampling locations; PML = PM sampling locations.

Each site had its own monitoring plan and each method had its own standard operating procedure, all reviewed and approved by the U.S. EPA. The on-site equipment installation and preliminary testing of all eight buildings was an arduous task that required 13 months to complete. Site PIs handled their own setups with up to one week's Purdue on-site help. The time between trailer delivery and valid data collection ranged from 50 to 235 d and averaged 129 d. The first day of valid data ranged from 6/1/07 (IN2H) to 1/1/08 (IN2B).

The NAEMS lasted three years and eight months after the first purchase of equipment. This time line included 13 months for purchasing equipment and setting up the monitoring instrumentation at the farms, 24 months to collect data, and eight months to decommission sites and prepare final reports. The 24-month duration assured that the project met the objectives of characterizing long-term emissions, which would also allow recording of variations due to seasonal effects, animal growth cycles, manure accumulation periods, and diurnal variations (Ni et al., 2011).

At each site, measurements were taken for ammonia (NH_3), hydrogen sulfide (H_2S), particulate matter (PM) and, to a more limited extent, VOCs. Carbon dioxide (CO_2) was measured even though it is not a regulated pollutant. An on-farm instrumentation shelter housed equipment for measuring pollutant concentrations at representative house air inlets and outlets, house airflows, operational processes, and environmental variables. A gas sampling system delivered selected gas sampling locations (GSL) to the gas analyzers and PM concentrations were measured at representative exhaust locations (PML) using real-time monitors (Table 1-11.1). Motion sensors monitored activity of hens and workers. Building airflow rate was assessed by monitoring fan operation and house static pressure, and air speeds through ventilation openings in the manure shed. Layer sites had 22% more sensors (Table 1-11.1), on the average, than other NAEMS sites.

Data was logged every minute and retrieved with network-connected PCs, formatted, validated, processed, and delivered to the U.S. Environmental Protection Agency (EPA). The predetermined data quality goal was to measure gas emissions with an uncertainty less than ±27% and PM emissions with an uncertainty less than ±32%. To help achieve data accuracy goals, numerous fan tests were conducted with a portable fan tester (Gates et al., 2004) to reduce airflow uncertainty, and gas analyzers were calibrated weekly. Another target of the study was to obtain valid data for 75% or more of the time (Table 1-21.2).

The emission data were submitted to the U.S. EPA between July 1 and 30, 2010 without discussion and data interpretation. The submitted data reports are being used by the EPA to propose emissions estimating methodologies, thus there was a need to provide further information and insight into the collected data.

Table 1-2. Number of valid days for emissions per site. Data completeness >75% in bold.

Site	NH_3	H_2S	PM_{10}	$PM_{2.5}$	TSP
IN2B	**626**	**639**	353	**28**	34
IN2H	518	363	407	13	19
NC2B	**613**	**638**	447	**27**	53
CA2B	**593**	**623**	**489**	**41**	34

Presented herein, the follow-on reports for each site provided additional information including statistical analyses, comparison of measured and historical weather parameters, static pressure frequency histograms, house inventories, plots of pollutant concentrations, tabulated summaries of hourly and daily averages, carbon dioxide concentrations and emissions, emissions per dozen eggs produced, emissions per hour of day, and general discussion of results including comparison with other studies, and regression-based prediction models. Uncertainty estimates are provided on a site-by-site basis, as are calculations using this data to estimate emissions levels relative to possibly applicable federal air emissions reporting requirements (in the form of number of hens required to reach the thresholds emissions rates that might create the reporting requirement). The purpose of the report is to provide the egg industry a practical document that details the findings of the layer portion of the NAEMS with aerial pollution emission data as well as the importance and meaning of these data.

1.4. Gas and PM Concentrations

The emissions were calculated by multiplying the house airflow times the difference in concentrations between the air leaving the house (exhaust) and the fresh air entering the house (inlet). Therefore, the concentration of the pollutant in the exhaust air does not indicate the level of emissions without taking the airflow into account. The accuracy of emission calculations increases with larger differences between exhaust and inlet concentrations, or with lower ratios of inlet to exhaust concentrations.

The average NH_3 concentrations at the layer sites were 27.7 ppm at the exhausts and 1.26 ppm at the inlets (Table 1-31.3). The ratios of overall average inlet to outlet NH_3 concentrations averaged 4.8% and ranged from 3.9 to 5.9%.

Table 1-3. Mean inlet and exhaust gas concentrations and inlet/exhaust ratios in percentage.

Site	Ammonia, ppm			Hydrogen sulfide, ppb			Carbon dioxide, ppm		
	Inlet	Exhaust	Ratio, %	Inlet	Exhaust	Ratio, %	Inlet	Exhaust	Ratio, %
IN2B	0.77	13.1	5.9	2.16	40.6	5.3	483	2,290	21.1
IN2H	1.95	50.4	3.9	8.66	25.7	33.7	494	1,779	27.8
NC2B	0.91	20.8	4.4	0.87	9.30	9.4	506	1,657	30.5
CA2B	1.40	26.6	5.3	2.40	22.4	10.7	474	1,030	46.0
Average	1.26	27.7	4.8	3.52	24.5	14.8	489	1689	31.4

The highest exhaust NH_3 concentrations were observed at the high-rise layer house in Indiana (IN2H), where all ventilation air flowed through large manure pits prior to exiting the house. At the belt-battery site IN2B, the ventilation exhaust flowed through manure drying tunnels attached to the exhaust fans. The inlet levels were higher at layer houses compared with pork and dairy because of several surrounding houses on-site and the extraordinary number of house sidewall fans at some of the sites.

The H_2S concentrations at the layer sites were relatively low because of the lack of anaerobic decomposition in solid manure as compared with liquid manure. The average H_2S concentrations were 25 ppb at the exhausts, and 4 ppb at the inlets. The ratio of mean inlet to outlet H_2S concentrations averaged 14.8% and ranged from 5.3 to 33.7%.

The average CO_2 concentrations at the layer sites were 1,689 ppm at the exhausts, and 489 ppm at the inlets, respectively. The ratio of mean inlet to outlet CO_2 concentrations averaged 31.4% and ranged from 21.1 and 46.0%. All the inlet concentrations were greater than the global atmospheric mean of 383 ppm because the inlets were on the farm site with abundant quantities of CO_2 emanating from exhaust fans on the farm.

The average PM_{10} concentrations were 484 $\mu g/m^3$ at the exhaust fans and 75 $\mu g/m^3$ at the ventilation inlets, (Table 1-41.4). The ratio of mean inlet to outlet PM_{10} concentrations in the houses averaged 15.5% and ranged from 7.8 to 19.2%. Both the highest ratio and the highest exhaust concentration occurred at the belt houses.

The average $PM_{2.5}$ concentrations were 63 $\mu g/m^3$ at the exhaust fans and 26 $\mu g/m^3$ at the ventilation inlets. The ratios of mean inlet to outlet $PM_{2.5}$ concentrations averaged 45.7% and ranged from 29.2 to 57.5%.

The average TSP concentrations were 1110 $\mu g/m^3$ at the exhausts and 72 $\mu g/m^3$ at the inlets. The ratio of mean inlet to outlet TSP concentrations averaged 6.4% and ranged from 4.6 to 7.9%.

Table 1-4. Mean inlet and outlet PM concentrations and inlet/exhaust ratios.

Site	PM_{10}, $\mu g/m^3$			$PM_{2.5}$, $\mu g/m^3$			TSP, $\mu g/m^3$		
	Inlet	Exhaust	Ratio, %	Inlet	Exhaust	Ratio, %	Inlet	Exhaust	Ratio, %
IN2B	108	627	17.2	33.0	113	29.2	113	1,620	7.0
IN2H	96	545	17.6	18.9	44.2	42.8	76.3	1,229	6.2
NC2B	36.0	464	7.8	23.0	40.0	57.5	41.0	885	4.6
CA2B	58.0	302	19.2	28.6	53.9	53.1	56.1	707	7.9
Average	74.5	484.5	15.5	25.9	62.8	45.7	71.6	1110	6.4

1.5. Emission Units

Emissions are reported in 1) annual total emissions per building, 2) average egg-specific emissions or emissions per dozen eggs produced, 3) average hen-specific emissions, 4) average LM-specific (LM=live mass in AU = 500 kg or 1100 lb live body weight), and 5) house-specific emissions. Annual and two-year emissions were used to compare annual emission variations.

1.6. Emissions of Ammonia

Ammonia emissions from houses at four layer sites were measured, and each¬ facility's¬ replicate¬ houses were averaged to yield a figure for the whole farm (Table 1-51.5). For the three high-rise sites, the 2-year mean emission rates ranged from 0.61 g/d-hen (CA2B) to 1.05 g/d-hen (IN2H). Compared with previous field monitoring results in Indiana, Iowa, Pennsylvania, and Ohio, the CA2B emission rate of 0.61 g/d-hen was the lowest (Table 1.6). The emission rate at NC2B (0.95 g/d-hen) was close to those at six high-rise houses in Iowa and Pennsylvania (Liang et al., 2005). The emission rate at IN2H (1.08 g/d-hen) was higher than the values from Liang et al. (2005), but lower than the long-term monitoring at four houses in Indiana and Ohio that ranged from 1.10 to 1.57 g/d-hen (Lim et al. 2004; 2008; Heber et al. 2005).

Table 1-5. Average daily mean hen-specific NH_3 emissions (g/d-hen) at layer sites.

Site	House 1	House 2	Manure shed	Farm
California (high-rise)	0.95	0.94		0.95
Indiana (high-rise)	1.02	1.14		1.08
N. Carolina (high-rise)	0.60	0.62		0.61
Average - high-rise	0.88			
Indiana (belt-battery)	0.28	0.28	0.01	0.29
Average - belt-battery	0.29			
Average all types	0.72			

The belt house emission rate of 0.29 g/d-hen at IN2B agreed with the emission rate (0.29 g/d-hen) from a 182-d study at a layer house in Ohio (Sun et al., 2005). Emission rates from four other manure-belt houses in Iowa and Pennsylvania (Liang et al., 2005) ranged from only 0.045 to 0.10 g/d-hen, about 16 to 34% of that from the IN2B and Ohio studies (Table 1-71.7). Another short term (6 d) study in the U.K. resulted in a higher emission rate (0.201 g/d-hen) than reported by Liang et al. (2005), but still lower than the IN2B and Ohio results.

Table 1-6. Comparison of NH3 emissions from commercial high-rise layer houses.

Location	Monitoring technique			Reported emission rate		Reference
	Duration, d	Ventilation	Concentration	Per AU, g/d-AU	Per hen, g/d-hen	
IN	182	Fan monitoring	NH_3 analyzer	509	1.57	(Lim et al., 2004)
IN	380	Fan monitoring	NH_3 analyzer	468	1.47	(Heber et al., 2005)
IN	380	Fan monitoring	NH_3 analyzer	342	1.10	(Heber et al., 2005)
IA	84	CO_2 balance	Drager sensor		0.84	(Liang et al., 2005)
IA	75	CO_2 balance	Drager sensor		0.95	(Liang et al., 2005)
IA	84	CO_2 balance	Drager sensor		0.81	(Liang et al., 2005)
IA	75	CO_2 balance	Drager sensor		0.80	(Liang et al., 2005)
PA	25	CO_2 balance	Drager sensor		0.88	(Liang et al., 2005)
PA	25	CO_2 balance	Drager sensor		0.78	(Liang et al., 2005)
OH	180	Fan monitoring	NH_3 analyzer	480	1.35	(Lim et al., 2008)
IN2H	518	Fan monitoring	NH_3 analyzer		1.05	NAEMS
NC2B	613	Fan monitoring	NH_3 analyzer		0.95	NAEMS
CA2B	593	Fan monitoring	NH_3 analyzer		0.61	NAEMS

Table 1-7. Comparison of NH_3 emission from commercial manure-belt layer houses.

Location	Monitoring technique			Emission rate		Reference
	Duration, d	Ventilation	Concentration	Per AU	Per hen, g/d-hen	
UK	6	Calculation only	Diffusion gas tube	2.7 g/h-AU	0.201*	(Nicholson et al., 2004)
IA	54	CO_2 balance	Drager sensor		0.045	(Liang et al., 2005)
IA	54	CO_2 balance	Drager sensor		0.062	(Liang et al., 2005)
PA	25	CO_2 balance	Drager sensor		0.10	(Liang et al., 2005)
PA	25	CO_2 balance	Drager sensor		0.087	(Liang et al., 2005)
OH	182	Fan monitoring	NH_3 analyzer	92.3 g/d-AU	0.29	(Sun et al., 2005)
IN2B	626	Fan monitoring	NH_3 analyzer		0.29†	NAEMS

*Converted from per AU emission rate, assuming 1.55 kg/hen body weight. †Including manure storage.

Table 1-81.8 lists other NH_3 emission rates at commercial layer houses in Europe and Asia. Because of the lack of detailed descriptions, the structures of these layer hen houses in six different countries might be slightly different from those of the NAEMS sites. However, with the assumption that the "deep litter" and "deep pit" houses reported by Koerkamp et al. (1998) and Nicholson et al. (2004) were equivalent to the high-rise sites, their emission rates of 0.631 to 0.919 g/d-hen were close to the emission rates at CA2B and NC2B.

Assuming the "battery" houses reported Koerkamp et al. (1998) were similar in structure with IN2B, the results from four European countries demonstrated profound variations, which ranged from 0.015 to 0.946 g/d-hen. The latter was 62 times higher than the former. The emission rates from the remaining four publications listed in Table 1-81.8 ranged from 0.104 to 1.15 g/d-hen (Wathes et al. 1997; Nicholson et al., 2004; Cheng et al., 2011; Dobeic and Pintaric, 2011). However, because of the different house structures, these values may not be directly compariable with the data from the NAEMS high-rise and manure-belt sites.

In addition to house type, e.g., high-rise vs. manure-belt, variations in NH_3 emission rates from field studies can also be affected by monitoring durations. Long-term and high-frequency monitoring that covers both diurnal and seasonal variations such as in the NAEMS can provide more reliable emission data. Figures 1.1 to 1.4 clearly display seasonal emission variations at all NAEMS layer hen sites. Short-term (e.g., several days) monitoring (Tables 1.6 to 1.8) could be equivalent to randomly picking up several daily data from the 2-year emission curves in Figures 1.1 to 1.4 and determining annual emission rates, obviously introduces bias.

Table 1-8. Comparison of NH_3 emissions from commercial layer houses of other types.

Location	Type	Monitoring technique			Emission rate		Reference
		Duration	Airflow	Concentration	Various units	g/d-hen	
UK	Deep litter	4 d	Heat/CO_2 bal.	NH_3 analyzer	30.9 mg/h-hen	0.742	(Koerkamp et al., 1998)
Holland	Deep litter	4 d	Heat/CO_2 bal.	NH_3 analyzer	36.0 mg/h-hen	0.864	(Koerkamp et al., 1998)
Denmark	Deep litter	4 d	Heat/CO_2 bal.	NH_3 analyzer	38.3 mg/h-hen	0.919	(Koerkamp et al., 1998)
UK	Deep-pit	7 d	Std rates	Diffusion tube	8.2 g/h-AU	0.631*	(Nicholson et al., 2004)
UK	Battery	4 d	Heat/CO_2 bal.	NH_3 analyzer	39.4 mg/h-hen	0.946	(Koerkamp et al., 1998)
Holland	Battery	4 d	Heat/CO_2 bal.	NH_3 analyzer	6.4 mg/h-hen	0.015	(Koerkamp et al., 1998)
Denmark	Battery	4 d	Heat/CO_2 bal.	NH_3 analyzer	7.7 mg/h-hen	0.018	(Koerkamp et al., 1998)
Germany	Battery	4 d	Heat/CO_2 bal.	NH_3 analyzer	2.1 mg/h-hen	0.050	(Koerkamp et al., 1998)
UK	caged	---	CO_2 bal.	NH_3 analyzer	9.2 g/h-AU	0.680*	(Wathes et al., 1997)
UK	Stilt	7 d	Std rates	Diffusion tube	1.4 g/h-AU	0.104*	(Nicholson et al., 2004)
Taiwan	Fans	4x summer 2x winter	Air speed	Flux chamber; Portable unit	0.42 kg/yr-hen	1.15	(Cheng et al., 2011)
Slovenia	Fans	n=1512	Air speed	Drager sensor	3.29 g/h-AU	0.60†	(Dobeic & Pintaric, '11)

* Converted from reported emission rates, assuming 1.55 kg hen weight.
† Converted from emission rate per AU using 3.8-kg hen mass reported by the authors.

Measurement technology is another critical factor that can affect monitored emission data. In mechanically-ventilated layer houses, direct monitoring of fan operation plus on-site fan testing, as conducted in the NAEMS, can offer more reliable airflow rate data than heat or gas balance methods. Continuous concentration determination using gas analyzers is currently the best NH_3 measurement method at animal facilities and can generate more accurate data than other sensors, such as diffusion gas tubes and electrochemical Drager sensors (Ni and Heber, 2008). Therefore, the NAEMS layer hen house monitoring produced higher quality data compared with those reported in the literature.

Moreover, variations between houses at each site were very small as a whole, indicating excellent reproducibility and high precision. The NAEMS indicated that on average, high-rise layer farms would need approximately 52,000 hens to generate 100 lb/d of NH_3. The corresponding figure for belt-battery-based facilities would be approximately 156,000 hens.

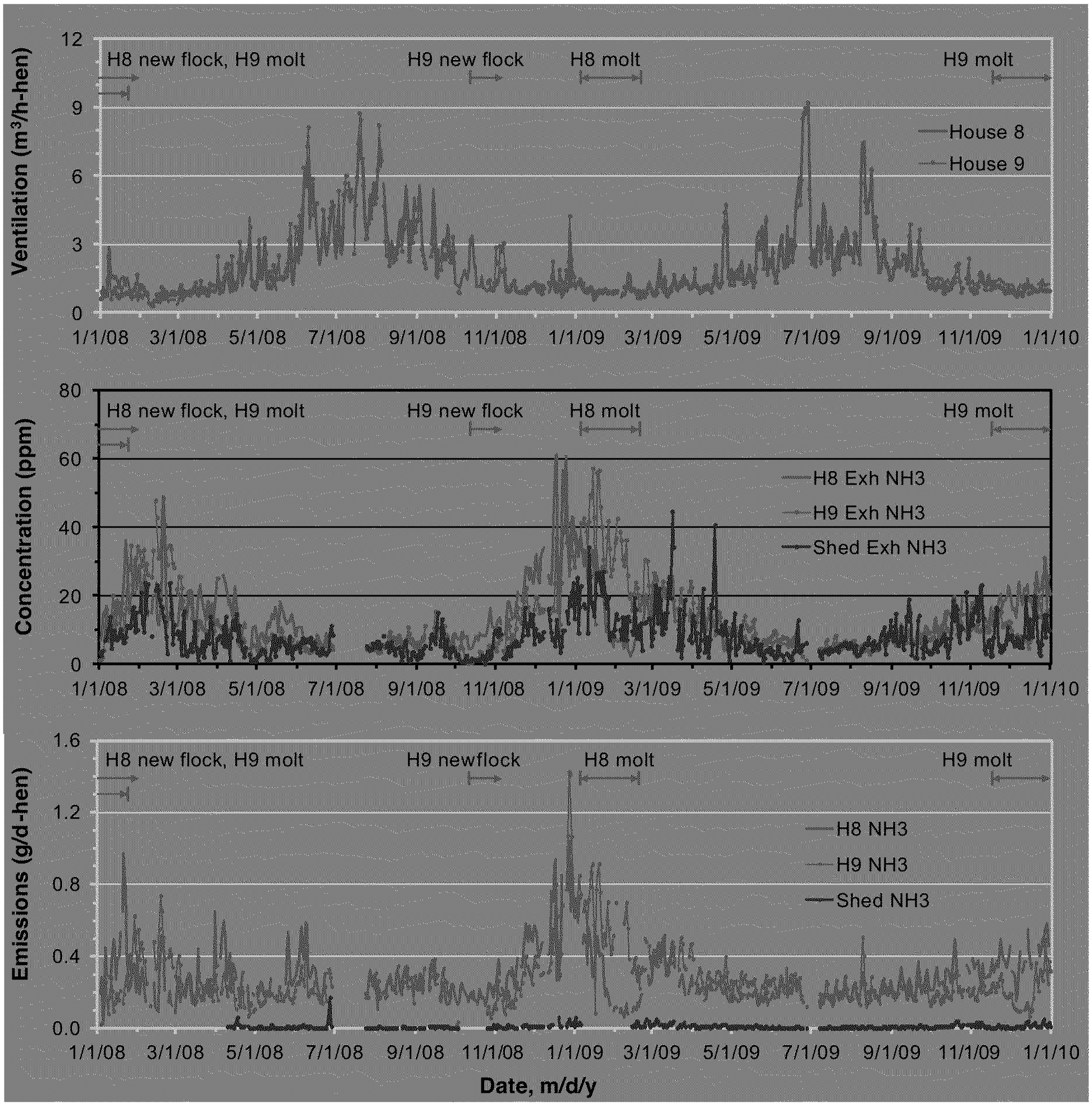


Figure 1.1. Daily mean house airflow, NH_3 concentration, and NH_3 emission at IN2B.

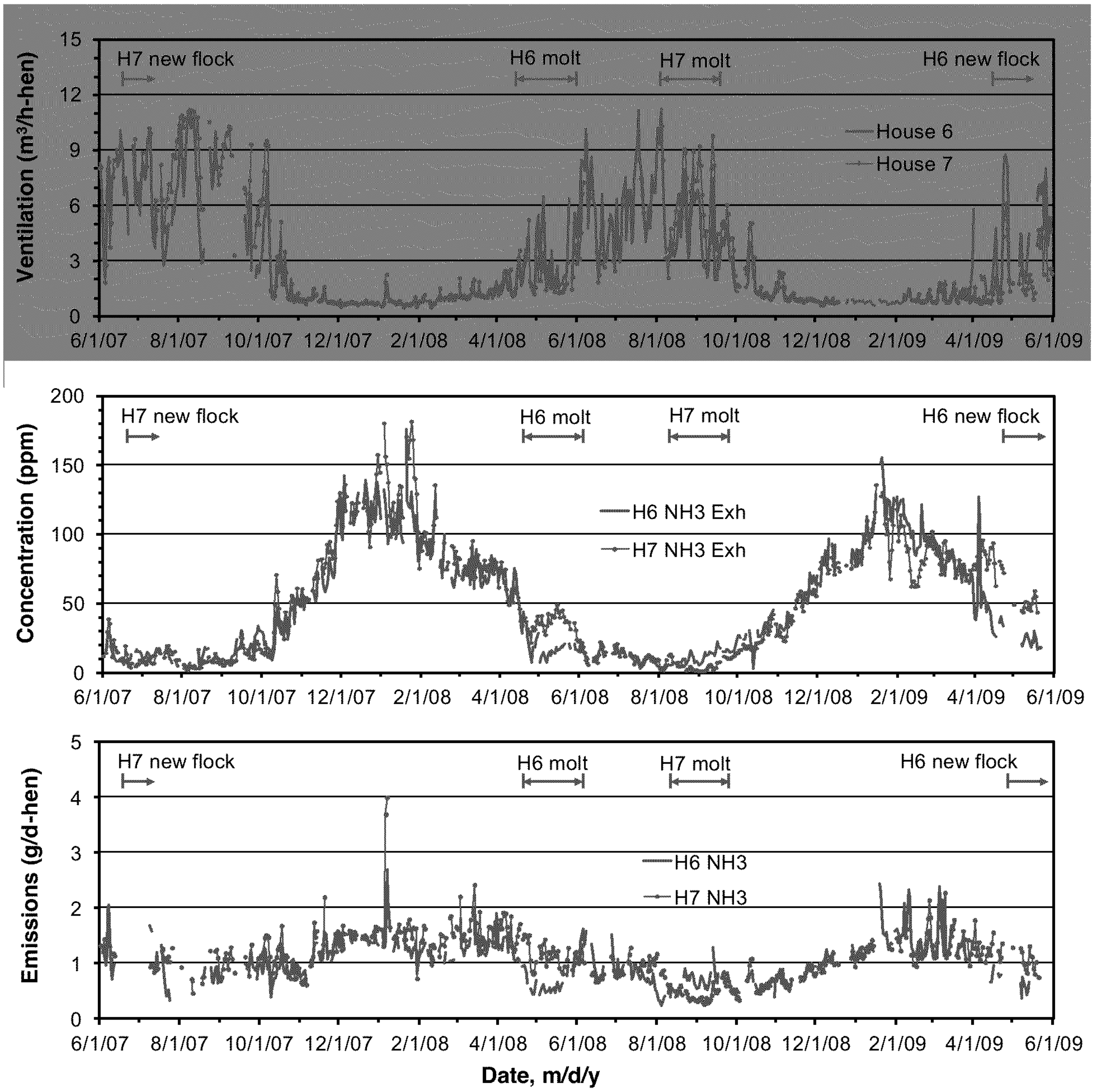


Figure 1.2. Daily mean house airflow, NH_3 concentration, and NH_3 emission at IN2H.

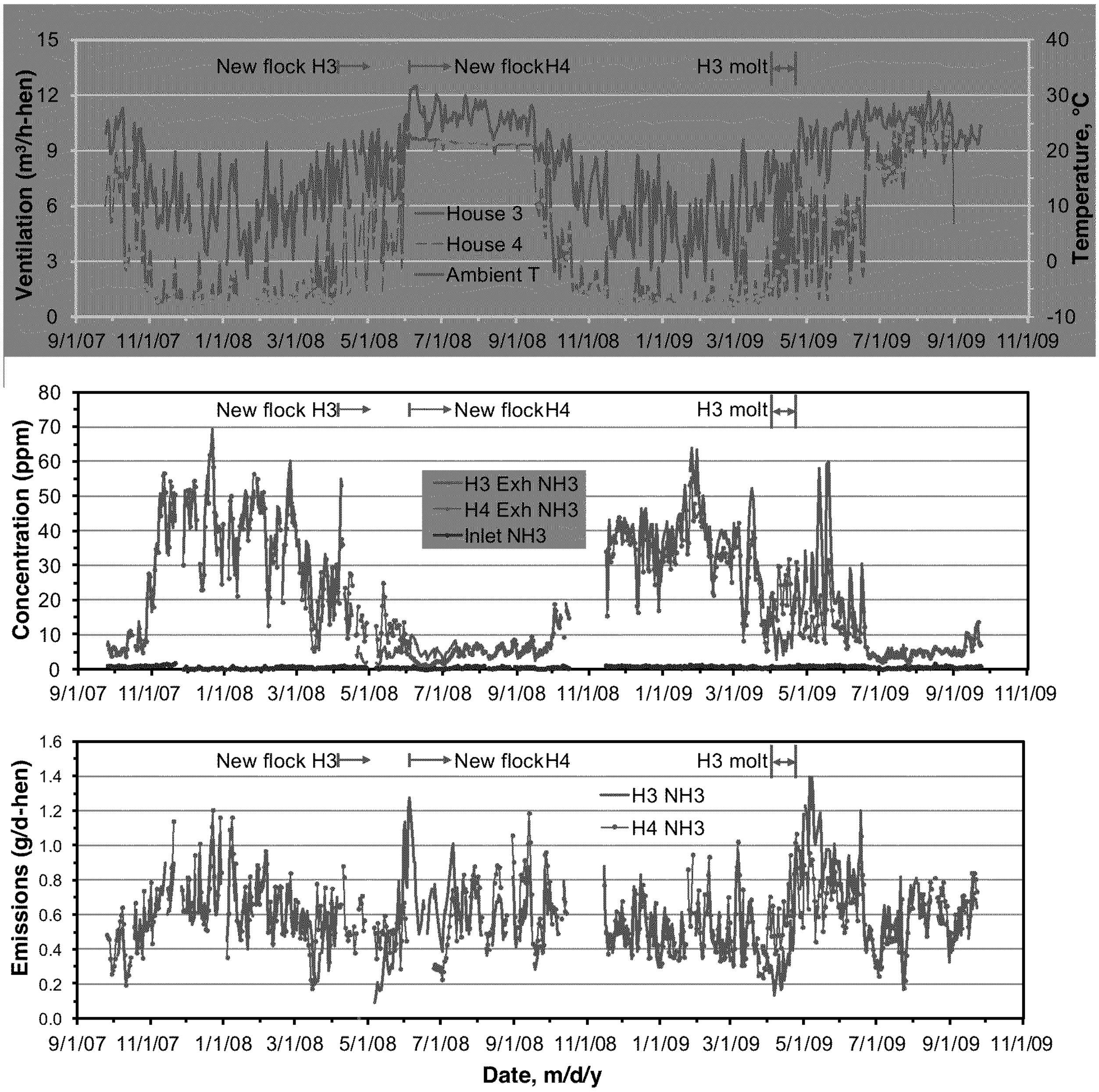


Figure 1.3. Daily mean house airflow, NH_3 concentration, and NH_3 emission at NC2B.

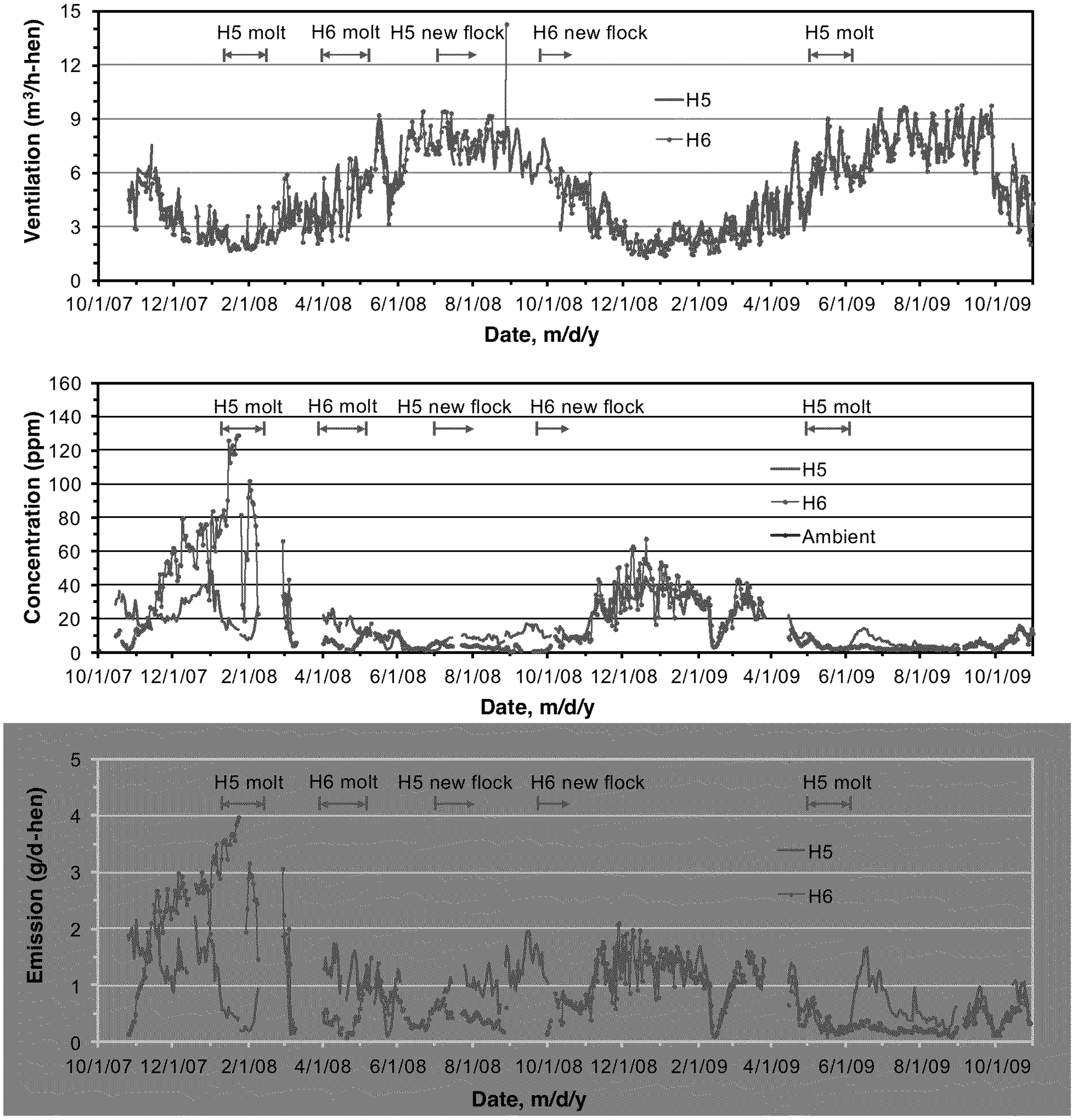


Figure 1.4. Daily mean house airflow, NH_3 concentration, and NH_3 emission at CA2B.

1.7. Emissions of Hydrogen Sulfide

At each of the three farms, reproducibility of H_2S emissions was very good, with both houses at each site deviating by approximately 5% or less of the mean for that site. Hen-specific H_2S emissions from the belt-battery site were about twice the average of the three high-rise sites. Among the three high-rise facilities, the pattern was similar to NH_3, in that NC2B had emission rates that were roughly half those of the IN and CA high-rise sites (Table 1-91.9). Very few parameters consistently correlated with H_2S emission rates.

Table 1-9. Average daily mean hen-specific H_2S emissions (mg/d-hen) at layer sites.

Site	House 1	House 2	Manure shed	Farm
California (high-rise)	1.33	1.20		1.27
Indiana (high-rise)	1.47	1.37		1.41
N. Carolina (high-rise)	0.61	0.68		0.65
Average - high-rise	1.11			
Indiana (belt-battery)	1.95	1.96	0.07	2.02
Average - belt-battery	2.02			
Average all types	1.34			

1.8. Emissions of PM_{10}

The PM_{10} emission rates from the IN and NC high-rise sites were nearly identical, averaging 20.7 mg/d·hen in Indiana and 20.1 mg/d·hen in North Carolina (Table 1-101.10). In contrast to NH_3 and H_2S, emissions the CA site was the outlier with regard to PM_{10}, as its emission rates were over 60% higher than the other sites.

The PM_{10} emissions were positively correlated with seasonal environmental variables (airflow, ambient temperature, relative humidity) at five of the six monitored high-rise houses (one of the two IN houses being the lone exception), and were negatively correlated with indoor and ambient RH in all high-rise houses. The CA high-rise site, by virtue of its warmer climate, had (on average) higher ambient temperatures, higher solar radiation levels, higher per-hen airflows and lower ambient humidities than either of the other sites, and lower indoor RH than the NC site (albeit slightly higher than the IN high-rise houses). These factors probably explain the higher PM_{10} emissions at the CA site, and imply that, in general, layer houses in warmer, drier climatic regions will emit more PM than cooler, wetter regions.

Table 1-10. Average daily mean hen-specific PM_{10} emissions (mg/d-hen) at layer sites.

Site	House 1	House 2	Manure shed	Farm
California (high-rise)	37.6	29.2		33.4
Indiana (high-rise)	16.9	22.6		19.8
N. Carolina (high-rise)	16.2	24.0		20.1
Average - high-rise	24.4			
Indiana (manure-belt)	12.4	25.2	0.3	19.0
Average - belt-battery	19.0			
Average all types	23.6			
Hutchings et al., 2009	47			

Emission rates of PM_{10} between the replicate houses at each site varied more than either NH_3 or H_2S. The relative standard deviations were 17.8%, 23.7% and 27.4% of the mean, respectively, for the CA, IN and NC high-rise facilities. This higher degree of house-specific variability means that the uncertainty associated with extrapolating the monitored houses to the whole farm is greater with PM than with NH_3 or H_2S.

1.9. Emissions of VOC

The annualized VOC emissions (extreme outliers removed and emissions adjusted to annual average temperature) ranged from 25.6 to 83.3 mg/d-hen from the eight houses (Table 1-111.11). Since the inlet concentrations were not measured to be subtracted as background, the gross VOC emissions were overestimates If the ratio of inlet to outlet concentrations of other gases are any indication, then it would be reasonable to estimate that the actual emission are around 90% of the gross emissions. Another caveat of these measurements and calculations is that they were based on a limited set of VOC samples that were collected over a period of several months in 2009.

Table 1-11. Annualized average hen-specific VOC emissions (mg/d-hen) at layer sites.

Site	House 1	House 2	Mean
California (high-rise)	76.3	66.3	71.3
Indiana (high-rise)	83.3	74.4	78.8
N. Carolina (high-rise)	-	25.6	25.6
Average - high-rise	58.6		
Indiana (belt-battery)	57.2	61.9	59.6
Average - belt-battery	59.6		

The top 10 compounds observed at the layer houses were as follows: pentane, iso-propanol, acetaldehyde, hexanal, 2-butanone, dimethyl-disulfide, toluene, 2,3-butanedione, dimethyl sulfide, phenol, pentanal, acetic acid, 4-methy-phenol, butanal, 1-butanol, heptanal, nonanal, octanal, and 2-pentanone.

1.10. Threshold Farm Sizes

The average mean numbers of hens that would potentially exceed the regulatory thresholds of EPCRA or the Clean Air Act are summarized in Table 1-121.12 where data are presented with only three significant figures which indicate the number to exceed emission threshold (NEET).

Based on the calculated NH_3 NEET's, all but the smallest operations (less than 50,000 hens) will most likely be required to report their NH_3 emissions. It is unlikely that any farm would be large enough to exceed the reporting thresholds for H_2S, although a very large farm with high S content in its water could possibly do so. The animal-normalized H_2S emission rate at the one NAEMS sow site with very high-sulfur water was an order of magnitude or more higher than at other swine site. If this were to hold true for layer sites, the number of hens required to reach the reporting threshold at a site with high-S water could be as low as a few million. There are probably no existing high-rise farms large enough to exceed the listed 250-tpy level for PM_{10}.

Based on the overall average emission of 58.6 mg/d-hen (Table 1-111.11), the mean VOC NEET for the three high-rise sites was 11,688,632 hens. The average VOC NEET for the belt houses in Indiana was nearly identical at 11,519,188 hens. The NAEMS indicated that on the average, layer farms would need at least 11.6 million hens to emit 250 tpy of VOC and 4.6 million hens to emit 100 tpy. The¬ NEET's¬ for¬ VOC¬ emissions¬ from¬ battery systems did not consider VOC emissions from the manure shed.

Assuming that inlet VOC concentrations were 10% of the exhaust concentrations as noted above, then the values in Table 1-111.11 are underestimates and the overall¬ VOC¬ NEET's¬ would¬ actually be 13.0 and12.8 million hens for the high-rise and manure belt houses, respectively.

Table 1-12. Summary of average mean NEET for NH_3, H_2S, PM_{10}, and VOC emissions.

Compound	NEET (number of hens)
High-rise systems	
Ammonia (100 lb/d)	51,600
Hydrogen sulfide (100 lb/d)	41 million
PM_{10} (250 tons/year)	27.7 million
VOC (250 tons/year)	11.7 million*
Manure-belt systems	
Ammonia (100 lb/d)	157,000
Hydrogen sulfide (100 lb/d)	22.5 million
PM_{10} (250 tons/year)	36.0 million
VOC (250 tons/year)	11.5 million*

*Based on gross emissions.

2. DISCUSSION OF CA2B DATA

2.1. Introduction

The farm was located in Stanislaus County, CA and was owned by Valley Fresh Foods, Inc. It is located 183 km (110 mi) from University of California-Davis (Davis, CA). The ranch had 24 layer houses in total, but the monitoring study was focused on the pod or cluster of high-rise layer houses in the southeast area of the ranch. The houses in this cluster, with two separate and individually-ventilated houses each, were of identical design and each house had capacity for 38,000 hens. The cluster initially consisted of three houses built in 2003, and a fourth house was added in the summer of 2008, during the monitoring period. Houses 5 and 6, which were part of H3, were selected as representative houses for this cluster (Table 2-12.1).

Table 2-1. Characteristics of houses at the California layer site.

Descriptive Parameters	Houses 5-6
House inventory	38,000 (per house)
House type	HR
Type of hens (genetics)	Lohman
Number of tiers of cages	5
Numbers of rows of cages	2
Type of cages	A-Valco
House width, m	14.9 (49 ft)
House length, m	129.3 (424 ft)
Ridge height, m	9.1 (30 ft)
Sidewall height, m	6.7 (22 ft)
House spacing, m	19.8 (65 ft)
Basement depth, m	2.4 (8 ft)
Manure collection method	Dropping boards/scraper
Manure scraping interval, h	24* (morning)
Ventilation type	MV – Sidewall Turbo
Number of pit circulation fans	0
Number of air inlets	1
Inlet type	Eave
Inlet adjustment method	Air doors
Inlet control basis	Pressure
Controls vendor/manufacturer	PMS
Walls with fans (N,S,E,W)	W (house 6), E (house 5)
Number of exhaust fans	12
Largest fan diameter, in.	122 (48 in)
Smallest fan diameter, in.	91 (36 in)
Fan spacing, ft.	Varies
Fan manufacturer	Aerotech
# ventilation stages	9
# temperature sensors	3
Summer cooling	Valco Systems misters

*3 to 4 times daily during five weeks of molting.

The distance between the houses was 20 m (66 ft). Each house was 129 m (423 ft) long, 7.5 m (25 ft) wide. The total house width was 15 m (49 ft). The basement, or manure storage pit was 2.4 m (8 ft) high, and the total building height was 6.7 m (22 ft).

The ventilation, feeding, and manure management systems of both houses were identical. Each house was mechanically ventilated in cross flow fashion with 12 single-speed exhaust fans on the first floor, consisting of two 91-cm fans and ten 122-cm fans. The fan speeds, house static pressure, temperature, and relative humidity, and outside weather variables were continuously monitored. All fans were evaluated with a portable fan tester three times during the test (Lin et al., 2012).

2.2. Quality Control and Quality Assurance

2.2.1. Gas Analyzers

2.2.1.1. INNOVA 1412 Carbon Dioxide Concentration

While carbon dioxide was not one of the regulated pollutants under study in the NAEMS, this measurement provides valuable information on ventilation performance (Heber et al 2006). It also provided a useful check on the integrity of the gas sampling system; readings of 100 ppm or higher in zero air during z/s checks were considered indicative of a leak in the sampling system.

Multipoint calibrations (MPCs), using zero gas and two (initial MPC) or three span concentrations were conducted five times to assess linearity. The initial MPC used 1000 and 2000 ppm span gas, whereas all other MPCs used 1200, 2400 and 3600 ppm CO_2, delivered via an Environics dilution system. The first two MPC tests were performed without humidification as per analyzer manufacturer instructions, thus the response by the instrument to the span gas was lower than expected.

The R^2 values for these tests without humidification were 0.983, when the response to zero gas was included in the MPC, but 1.00 when the linearity of the applied span gases was analyzed. Therefore, the instrument was deemed precise from the start of the study to 1/15/08 when the remaining MPCs were conducted with humidification, and resulting R^2 values were 1.00, with the zero response included in the linearity test. A linear relationship between input CO_2 concentration and analyzer response was therefore assumed for at least the range of 0 to 3600 ppm.

Precision checks were performed periodically using zero gas and a span gas. The span gas concentration was 1990 ppm until 1/28/08, after which 2390 ppm was the applied span. Based on the zero and span precision checks, two linear models were generated to correct the gas analyzer measurements and reduce measurement bias caused by the gas sampling system (Table 2-22.2Table 2-22.2).

Table 2-2. Concentration correction periods for carbon dioxide.

Start/end dates	# of checks		Linear model	Measurement accuracy Relative to Span, %			
				Bias		Precision	
	Zero	Span		z	s	z	s
10/10/07 – 10/15/08	18	19	y = 0.989x – 17.60	0.2	0.3	0.1	1.9
10/15/08 – 11/1/09	18	18	y = 1.051x – 47.33	-0.1	0.1	0.4	1.2
All	36	37		0.0	0.2	0.3	1.5

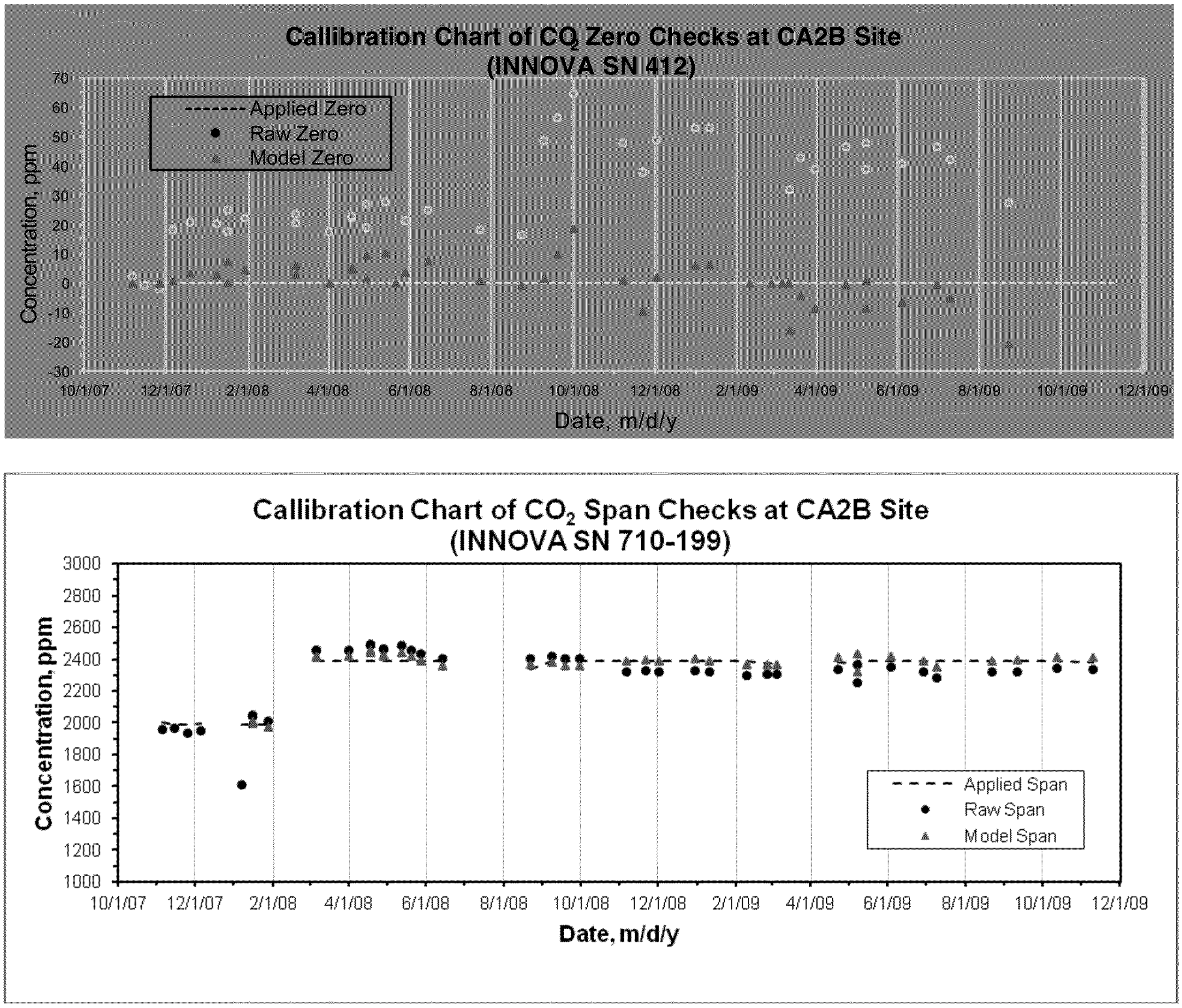


Figure 2.1. Calibration checks of the CO_2 measurements.

2.2.2. Particulate Matter Analyzers

2.2.2.1. Tapered Element Oscillating Microbalances

Collocated PM_{10} measurements were collected in one house for a two-hour period. The percent difference between the two sensors was 5.3% (Table 2-32.3), and the fluctuations in 1-min concentration measurements (Figure 2.2) were similar. The average concentrations during the collocation period were higher than the mean concentrations for both houses (326±157 and 277±163 µg·dscm (GA2B EPA Report), but well within the range of measurements collected over the two-year monitoring period.

Table 2-3. TEOM collocation test results.

PM type	n, min	Average concentration, $\mu g\ m^{-3}$		Difference, %
		House 2 TEOM	House 1 TEOM	
PM_{10}	121	506	481	5.3

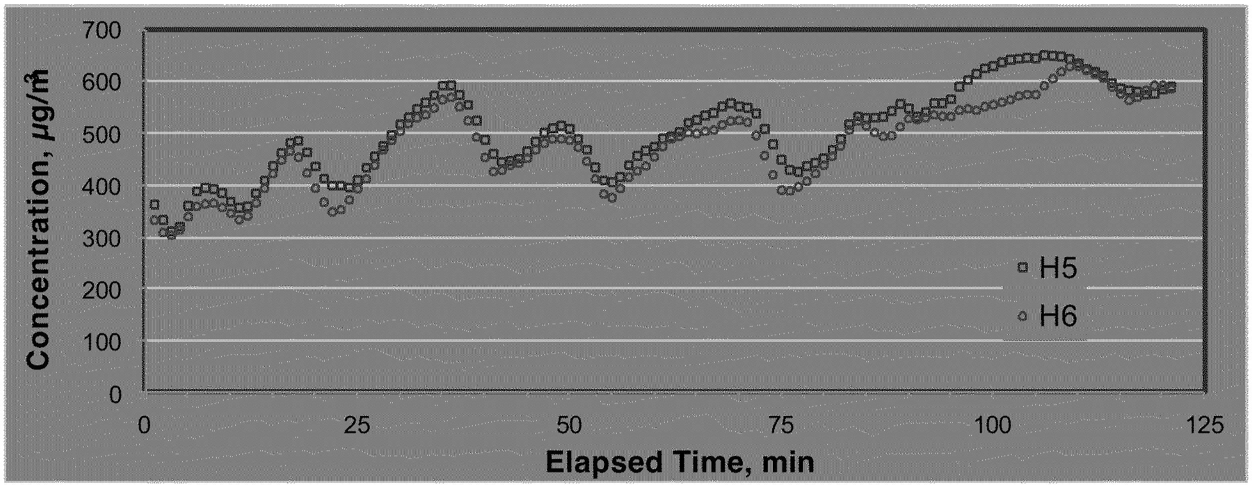


Figure 2.2. Results of pair wise collocation of PM_{10} measurements by the two TEOMs.

2.3. Data Analysis

2.3.1. Data Corrections, Substitutions & Calculations

2.3.1.1. Animal Inventory & Weight

Weekly layer inventory, hen mass, feed and water consumption, and egg production and characteristics were collected from the farm's computer system for the Each weekly total egg production was divided by seven to approximate the daily egg production rate for each house. The layer inventory and hen mass were interpolated between the weekly reported values.

2.3.1.2. Emission Rate Differences Between Active and Inactive Production Periods

This report includes a comparison of house-specific emission rates between active periods of production, and those periods when the house was empty between flocks and cleaning was occurring, and during molt. Table 2-42.4 describes the periods that were averaged together. The days of production period changes, like the days the hens were shipped out, were excluded. While Table 2-42.4 describes the total number of days within each production period, the completeness for the different periods was affected by instrument status, maintenance and movement (i.e. moving sensors during house cleaning activities).

Table 2-4. Description of production periods.

Production period	House	Number of days	Dates
Active	H5	656	10/17/07-1/4/08
			2/10/08-6/2/08
			6/28/08-5/8/09
			6/7/09-10/31/09
	H6	684	10/17/07-3/21/08
			4/27/08-8/27/08
			9/23/08-10/31/09
Molting	H5	61	1/6/08-2/8/08
			5/10/09-6/5/09
	H6	34	3/23/08-4/25/08
Cleaning; Empty House	H5	22	6/5/08-6/26/08
	H6	23	8/30/08-9/21/08

2.3.1.3. *Emissions per Dozens of Eggs Produced*

An additional description of total average emission per dozen eggs marketed (egg-specific emission) is included in this report. The daily mean (DM) house-specific emission rates were divided by the respective daily egg production rate for the given house. The average DM egg-specific emission rate is presented.

2.3.1.4. *Emissions per Farm*

The total annual emission for the cluster of four buildings (eight houses) in the southeast corner of the farm is presented for the various pollutants, assuming the average emissions and environmental conditions of the monitored houses also represent the average conditions in the remaining three buildings.

2.3.1.5. *Nitrogen Balance*

A nitrogen (N) balance was conducted to compare the amount of N entering and leaving the house in various forms as a check on the ammonia (NH_3) emission calculations. Ideally, the balance would sum to zero. However, the end result depends on the quality of data used for all forms of N movement; as noted in this section, several assumptions were made and the frequency of nutrient content measurements contribute to the lack of balance. However, this balance provides a good overview of how and where N entered and left the system, and the approximate relative contribution of each balance component.
One overall N balance was prepared for the period 8/20/08 to 2/10/08 for H5, and 9/21/08 to 2/10/08 for H6. The start dates corresponded to manure removal from H5 and the placement of a new flock in H6. The end date corresponds to manure removal from both houses.

Daily feed intake was reported on a weekly basis by the farm's
content of the feed was assessed in September 2009 and reported in the CA2B EPA Report. Four feed samples were also collected in August 2008; the average (±SD) total N content of these samples was 2.74% (0.20%). The August 2008 average was used in the N balance. The multiplication of total feed intake and N content of the feed provided the input, or positive component, of the feed to the nutrient balance.

The N input via the drinking water was assumed to be negligible, based on total N < 7 mg/L.

The amount of N leaving the house as hen mortalities was estimated using the difference in inventory between the end and start dates, an average carcass mass of 1.7 kg, and an approximate body N composition of 20%. The mortality N was considered an output, or negative component, to the nutrient balance.

For the balance periods, the daily mean NH_3 emission data were used to assess the total loss of N (14/17 times the total NH_3 loss) via the air. There were valid daily NH_3 emission estimates 85 and 96% of the time for H5 and H6, respectively. During periods of missing measurements, the average daily mean (ADM) emission was interpolated based on the first measurements immediately preceding and proceeding the missing measurement(s). The air emissions were an output, or negative component of the nutrient balance.

During manure removal, nutrients are removed from the house. The volumes of manure removed, as reported by the producer, were 676 and 436 m^3 from H5 and H6, respectively. The site personnel measured the H5 and H6 manure density as 0.44 and 0.37 kg L^{-1}, respectively. The TKN content of the loadout manure was assessed during the 2/10/09 loadout, as shown in the CA2B EPA Report. From these measurements, the nutrient content of the manure removed was estimated, and shown as an output in the balance.

The nutrient balances are presented on a total N basis, and relative to N intake via the feed.

2.3.1.6. Statistical Analyses

Key factors for pollutant production were evaluated in an intensive multiple variable regression analysis using the procedure PROC GLMSELECT with Statistical Analysis Software (SAS 9.2; SAS Institute Inc., Cary, NC, USA), based on the STEPWISE selection.

A simplified multiple variable regression analysis with room temperature and live mass density, (using the SAS procedure PROC GLMSELECT, based on the STEPWISE selection with SELECT=CP and CHOOSE=ADJRSQ) was used to generate prediction equations based solely on these variables.

Linear regression was also performed between hourly pollutant emission averages and individual key factors. The correlation between pollutant emission rates is presented in a separate section.

2.4. Results

2.4.1. Weather Conditions

Historical temperature and wind data (Table 2-52.5) were obtained from Modesto, CA, which is approximately 21 miles northwest of the site. The monthly mean temperatures from the two-year NAEMS dataset were within 2ºC of the monthly averages for Modesto (Figure 2.3).

Table 2-5. Monthly averages for weather conditions in the area*.

Month	Temperature*,°C			Wind speed km h^{-1}	Wind direction
	High	Low	Mean		
January	12	3	8	13	SE
February	16	5	12	13	SE
March	19	6	14	15	WNW
April	23	8	17	15	WNW
May	28	11	20	17	W
June	32	14	23	18	W
July	35	16	26	16	WNW
August	34	16	25	15	WNW
September	31	14	23	14	WNW
October	26	10	18	12	WNW
November	17	6	12	12	SE
December	12	3	8	13	SE
Annual Average	24	9	17		

* http://www.weather.com/weather/wxclimatology/monthly/USCA0714\

The monthly average measured wind speed (Figure 2.4) pattern was very similar to the historical averages throughout the entire NAEMS. However, the wind speed measurements differed by approximately 5 km h^{-1} (3 mph). The NAEMS measurements were collected from a 3-m tower on the ridge of the monitored house and likely influenced by neighboring structures.

2.4.2. Animal Characteristics

From weekly producer-maintained production records, the hen inventory (Figure 2.5) and mass were gathered and used to determine the stocking density (Figure 2.6). The average hen mass varied between 1.2 and 1.4 kg during molt and new cycle start-up periods. During production periods, the average hen mass was 1.6 to 1.8 kg. The resulting stocking densities were at or above Animal Husbandry Guidelines of 67 to 86 in^2/hen (UEP, 2010).

Figure 2.7 illustrates the drop in egg production during molt, and the subsequent increase in egg production compared with before molting through use of this practice.

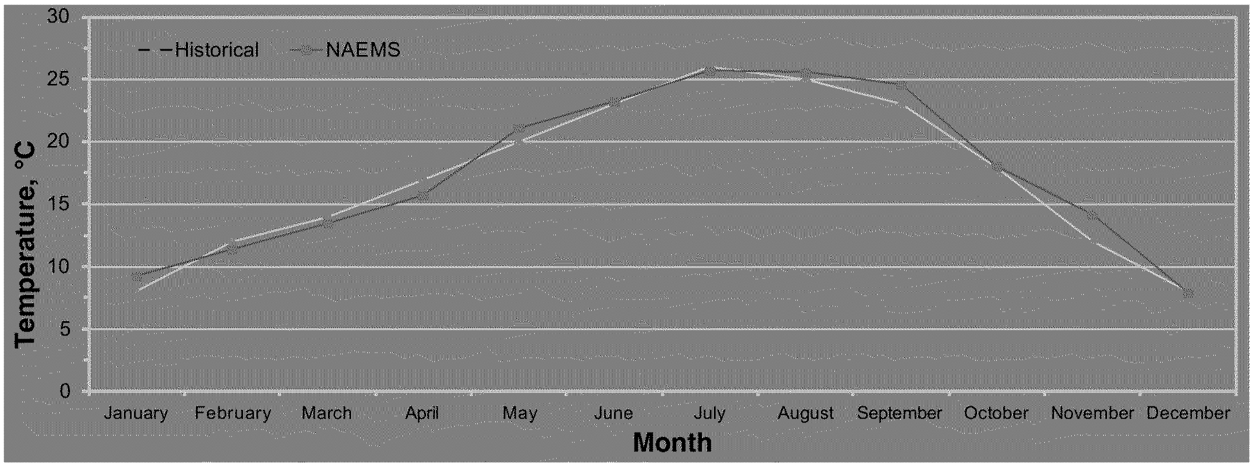


Figure 2.3. Historical and NAEMS monthly mean temperatures.

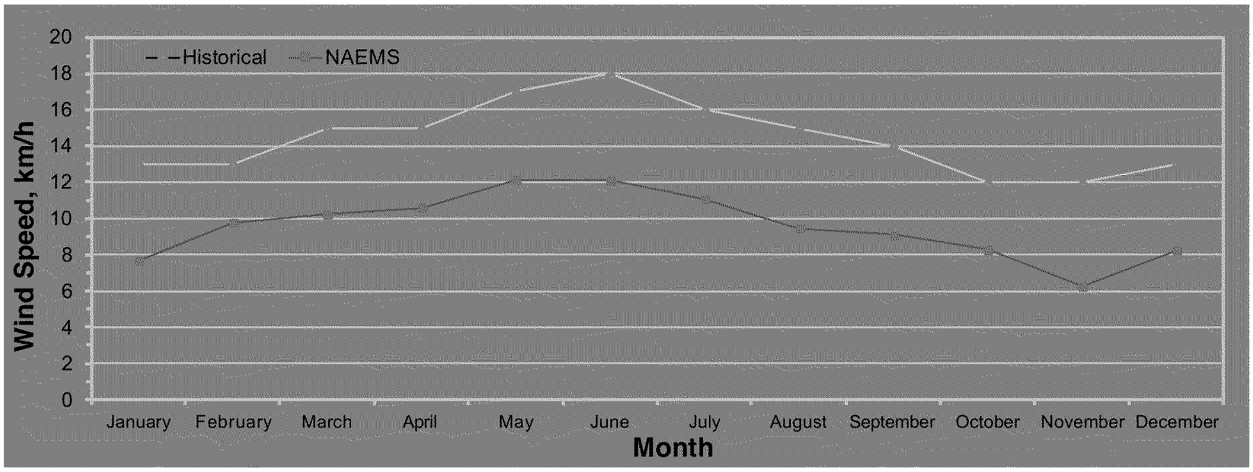


Figure 2.4. Comparison of historical average and NAEMS wind speeds.

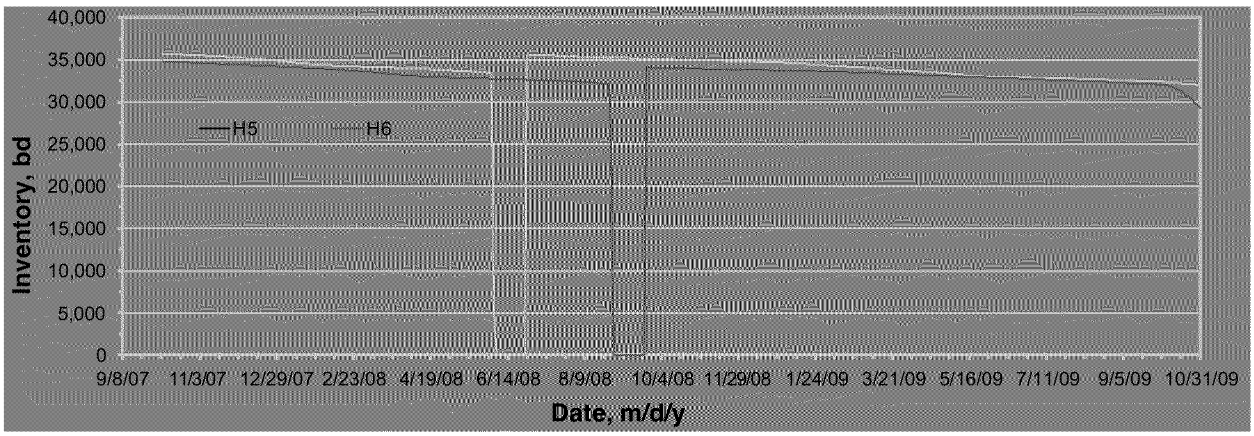


Figure 2.5. Daily mean hen inventory.

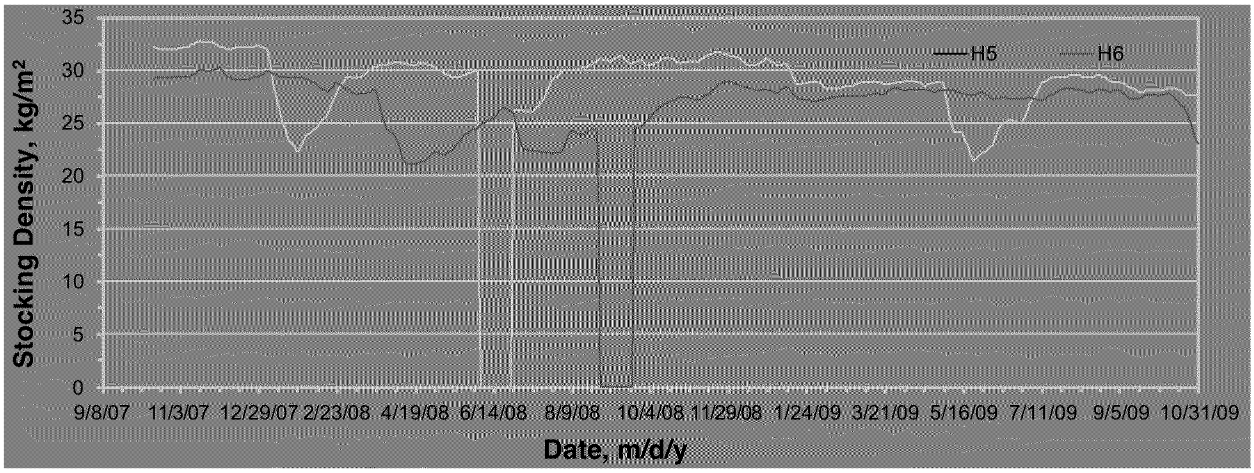


Figure 2.6. Daily mean live mass density in the houses.

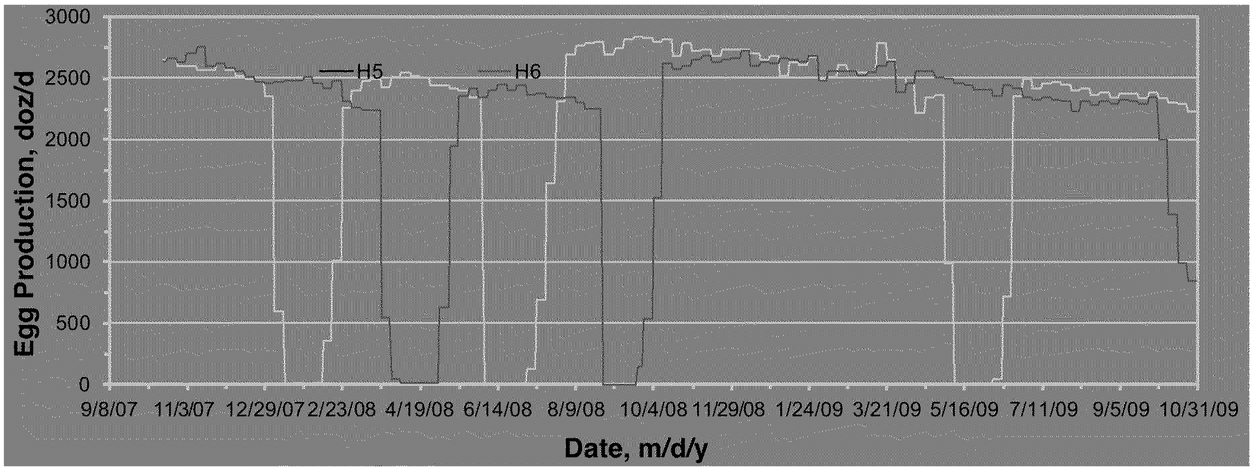


Figure 2.7. Daily mean egg production in each house.

2.4.3. Environmental Conditions and Airflow

2.4.3.1. House Conditions

Figure 2.8 presents the daily mean relative humidity data for each house, and for the inlet/ambient outdoor sampling point. The indoor RH exceeded the inlet RH during the summer months, likely a result of mister use in the inlets to evaporatively cool the incoming air.

Static pressure distributions for each house (Figure 2.9 and Figure 2.10) indicate 87 to 90% of measurements were between -15 and -30 Pa, indicating the ventilation system was effective in maintaining static pressure in the optimum zone for airflow. Less than 3% of the static pressure measurements were positive, which typically occurred when fans were not operational between flocks. Airflow data (and thus emission) were not calculated when house dP was positive because the total flow exiting the building could not be accurately determined; however, less than 3% of the airflow/emission data was excluded for this reason.

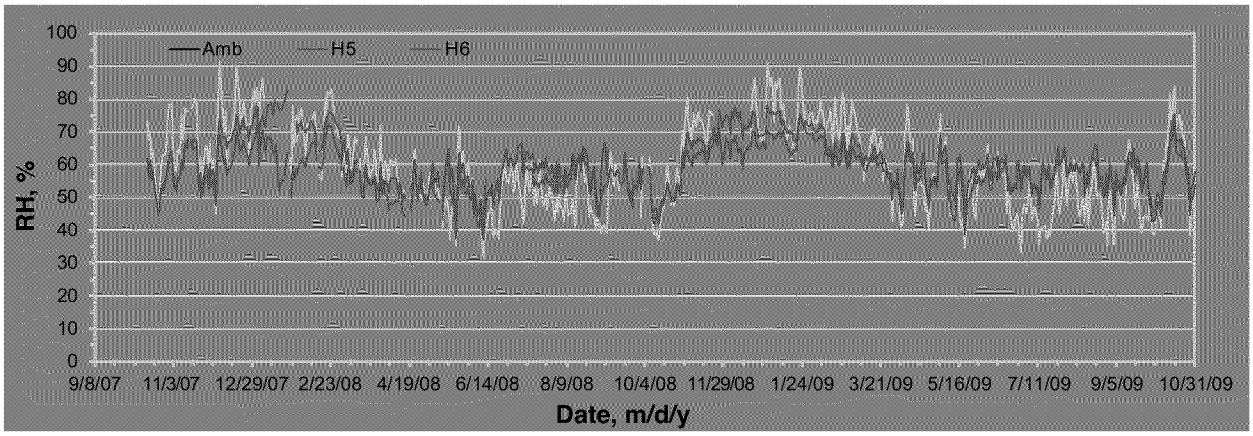


Figure 2.8. Daily mean indoor and outdoor relative humidity.

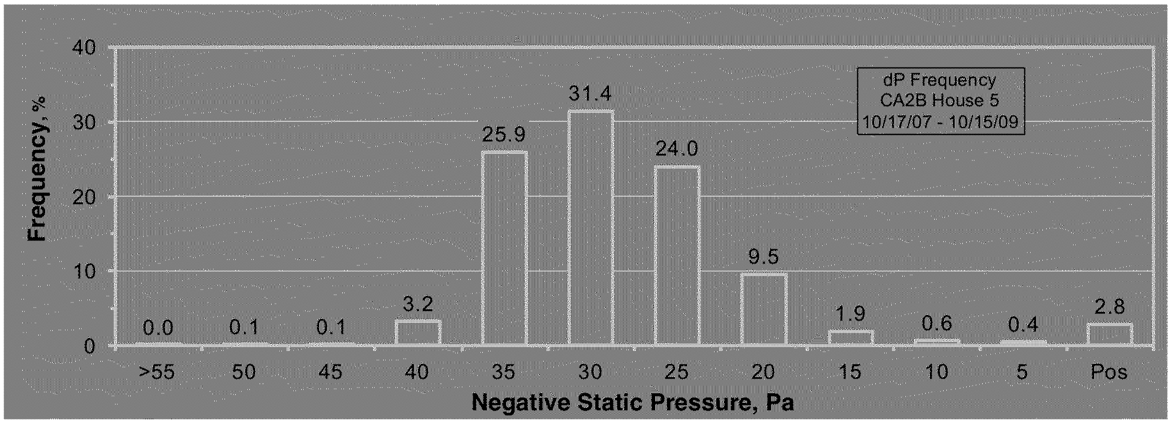


Figure 2.9. Histograms of the static pressure differential distributions in house 5.

Fan airflow models were developed from fan test data to calculate fan airflows based on static pressure and fan speed. Results showed that fan performance factors of the 91- and 122-cm fans were 75 and 84% of airflows of lab-tested models of newly manufactured fans, respectively. The DM house ventilation rate averaged 47 m^3 h^{-1} and ranged from 12 to 88 m^3 h^{-1}. The ADM ventilation rate was 5 m^3 h^{-1} hen^{-1} and ranged from 1.3 to 9.8 m^3 h^{-1} hen^{-1}. Relative uncertainties of the ventilation rates averaged ±4.8% and ranged from ±2.9 to ±8.8%. Models of ventilation rate were developed based on inlet and exhaust temperatures (Lin et al., 2012).

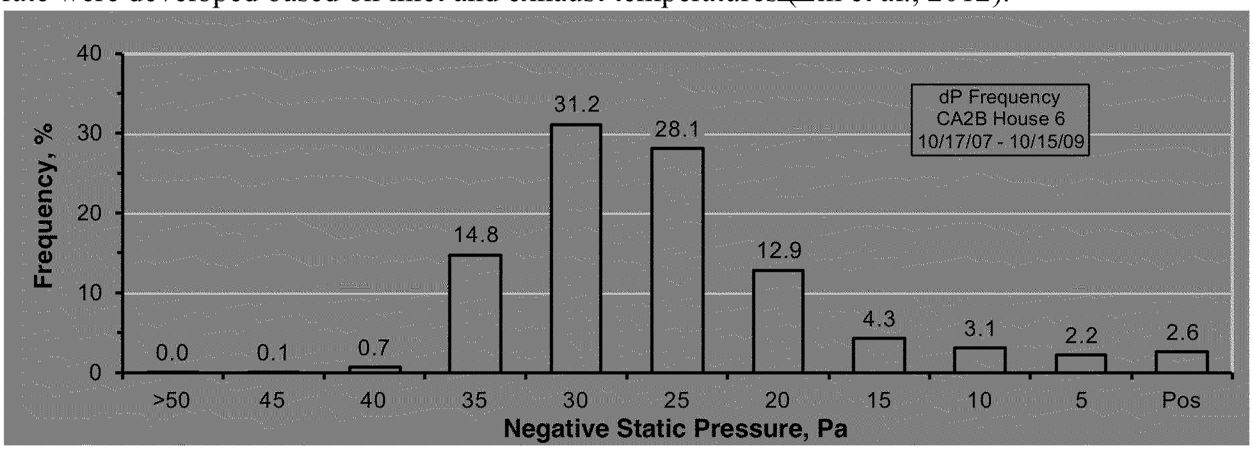


Figure 2.10. Histograms of the static pressure differential distributions in house 6.

Figure 2.11 and Figure 2.12 show daily mean ventilation rates in H5 and H6, respectively. The house temperature in H5 averaged 25.4°C and ranged from 20 to 33 °C from 6/3/08 to 7/27/08 were zero because spent hens were removed. House 6 had a similar result when the inlet temperature ranged from 4.4 to 32.1°C. The ventilation rates but the temperatures inside both houses had slightly different patterns (Figure 2.12).

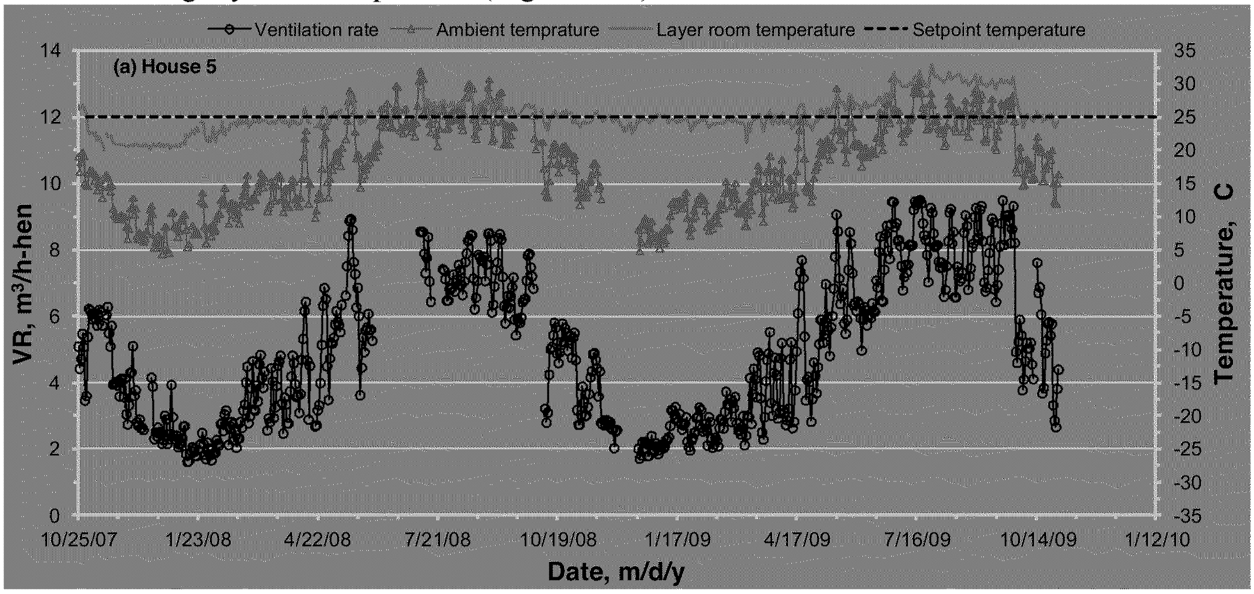


Figure 2.11. Daily mean ventilation rates and temperatures in H5 (Lin et al., 2012).

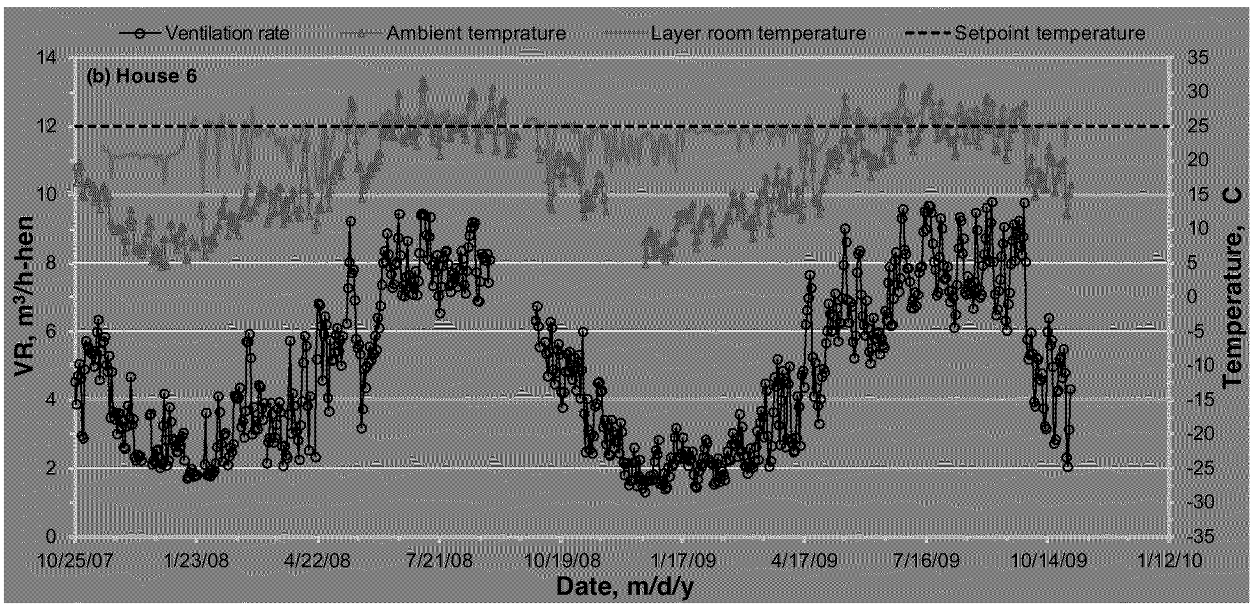


Figure 2.12. Daily mean ventilation rates and temperatures in H6 (Lin et al., 2012).

Figure 2.13 presents a high correlation between DM inlet temperature and DM house ventilation rate. Figure 2.14 plots the absolute and relative uncertainty of house ventilation rate at a 95% confidence interval.

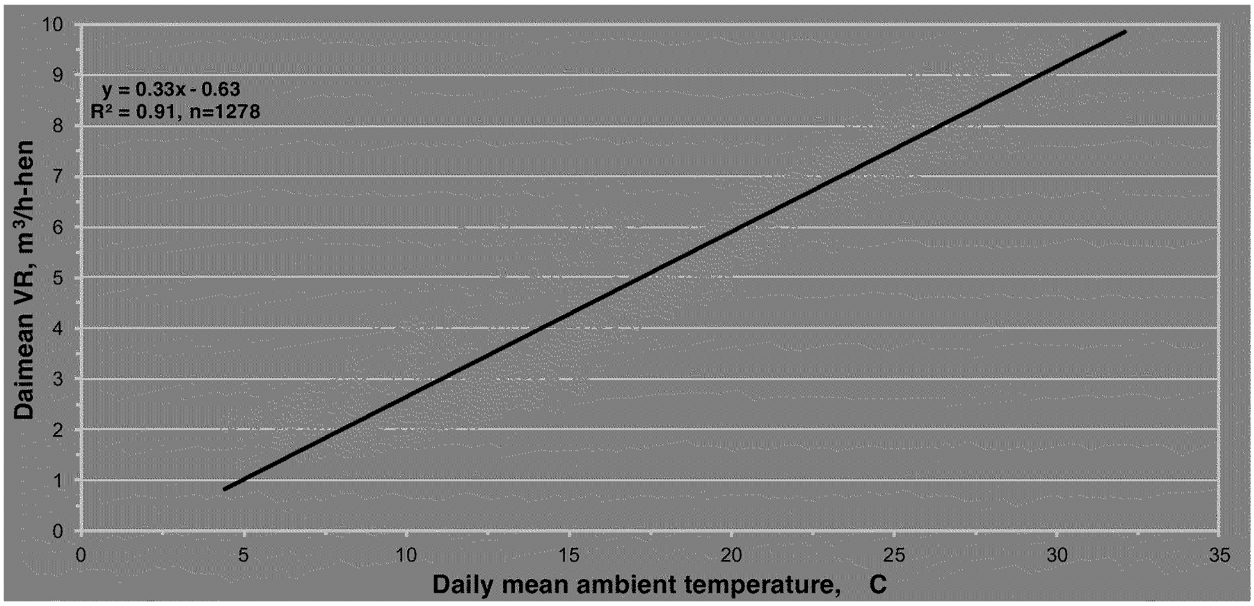


Figure 2.13. Influence of temperature on daily mean ventilation rates (Lin et al., 2012).

2.4.4. Particulate Matter Concentration and Emission

2.4.4.1. TSP Concentration and Emission

Total suspended particulate (TSP) measurements were collected during seven periods totaling up to 44 d for both exhaust and inlet conditions (Table 2-62.6 and Figure 2.15).

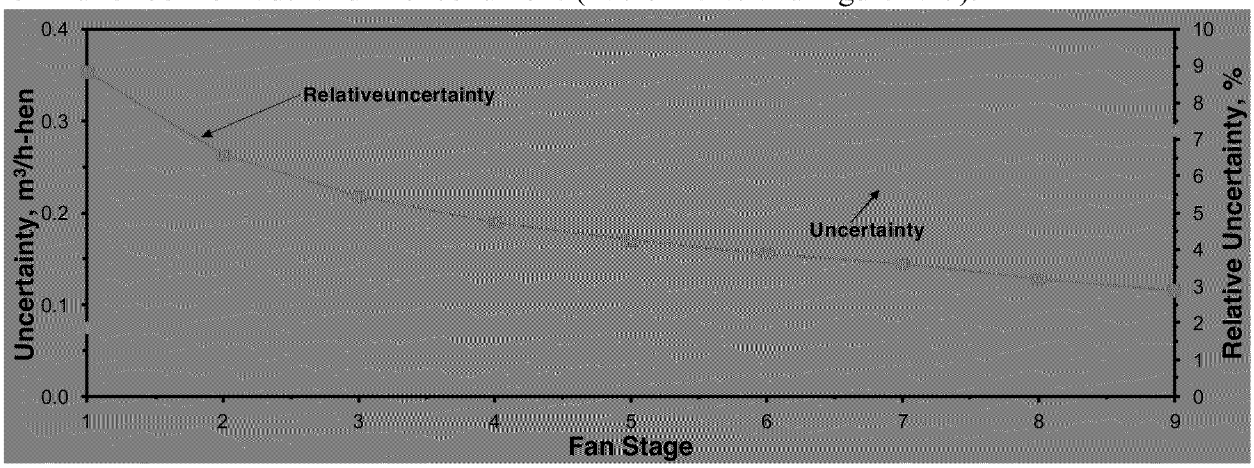


Figure 2.14. Absolute and relative ventilation uncertainties at 95% CI (Lin et al., 2012).

Table 2-6. Characteristics of inlet and exhaust TSP concentrations (µg dsm^{-3}).

Variable	Inlet	House 5	House 6
Daily means			
Average	56	627	787
SD	56	368	543
n	37	40	44
Minimum	15	58	19
Maximum	285	1480	2400
Hourly means			
Average	56	635	777
SD	85	593	712
n	991	1084	1157
Minimum	-1	-98	-176
Maximum	1028	5579	5345

The summary TSP emission data are shown in Table 2-72.7 and Figure 2.16 to Figure 2.18. Roumeliotis and Van Heyst (2008) summarized reported emission factors for layers. The range of TSP emission rates for battery cage systems ranged from 15.3 g $d^{-1}AU^{-1}$ in Europe to 63 g $d^{-1}AU^{-1}$ in Indiana. The LM-specific emission rates were 21.0 and 26.6 g $d^{-1}AU^{-1}$, within the range of reported values. Roumeliotis and Van Heyst (2008) concluded that the range in reported emissions was likely related to climate, ventilation and manure management.

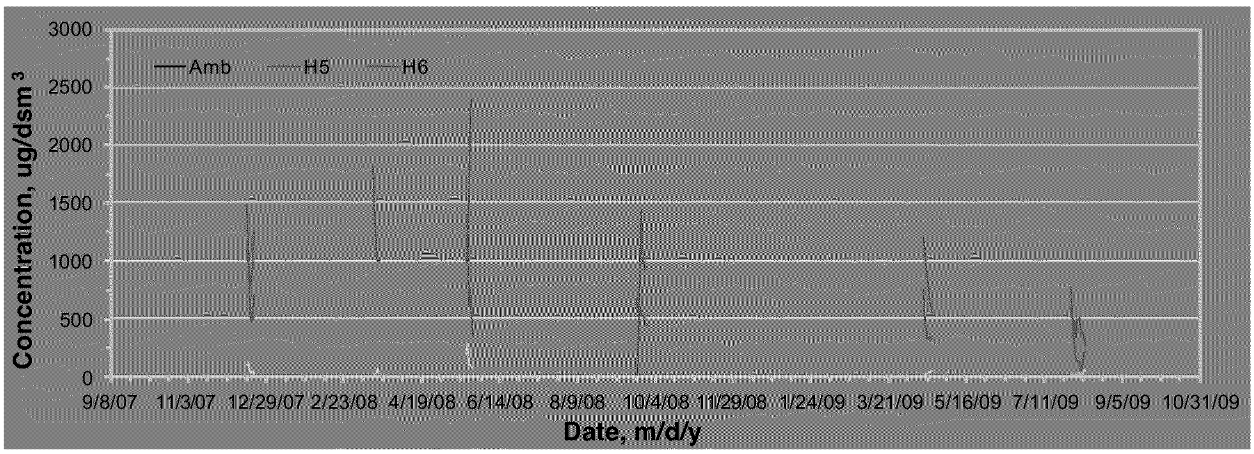


Figure 2.15. Daily mean TSP concentrations.

Table 2-7. Average means±SD (n) of TSP emission rates.

Variable	House 5	House 6
Daily mean emission rate		
House-specific, g d^{-1}	2437±1382 (36)	2764±1456 (32)
Area-specific, mg d^{-1} m^{-2}	1250±709 (36)	1418±746 (32)
Hen-specific, mg d^{-1} hd^{-1}	72±41 (36)	84±44 (32)
LM-specific, g $d^{-1}AU^{-1}$	21.0±12.0 (36)	26.6±16.4 (32)
Egg-specific, mg d^{-1} doz^{-1}	992±593 (36)	1184±621 (32)
Hourly mean emission rate		
House-specific, g d^{-1}	2388±2624 (973)	2663±2576 (842)
Area-specific, mg d^{-1} m^{-2}	1225±1345 (973)	1366±1321 (842)
Hen-specific, mg d^{-1} hd^{-1}	70±78 (973)	82±78 (835)
LM-specific, g $d^{-1}AU^{-1}$	20.5±22.7 (973)	25.8±26.3 (835)

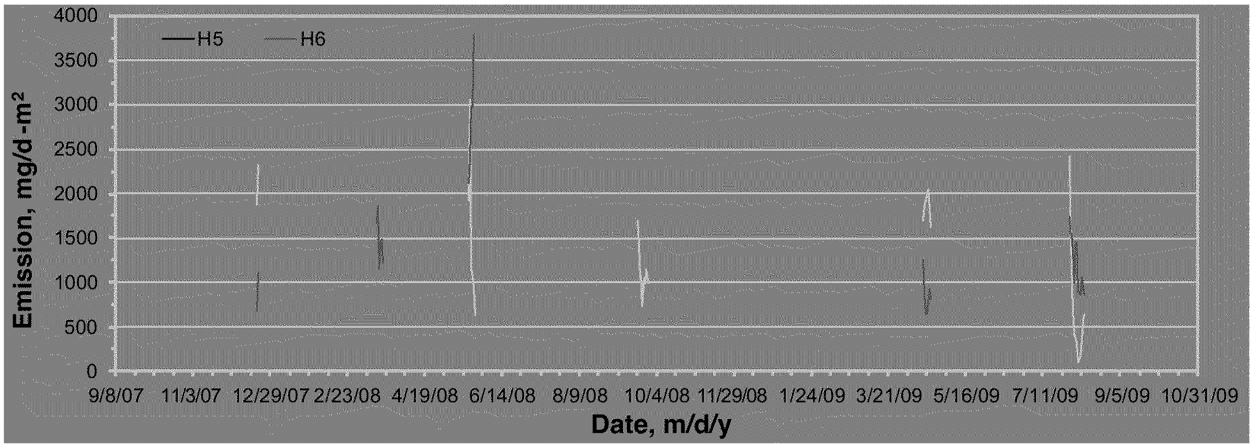


Figure 2.16. Daily mean area-specific TSP emission rates.

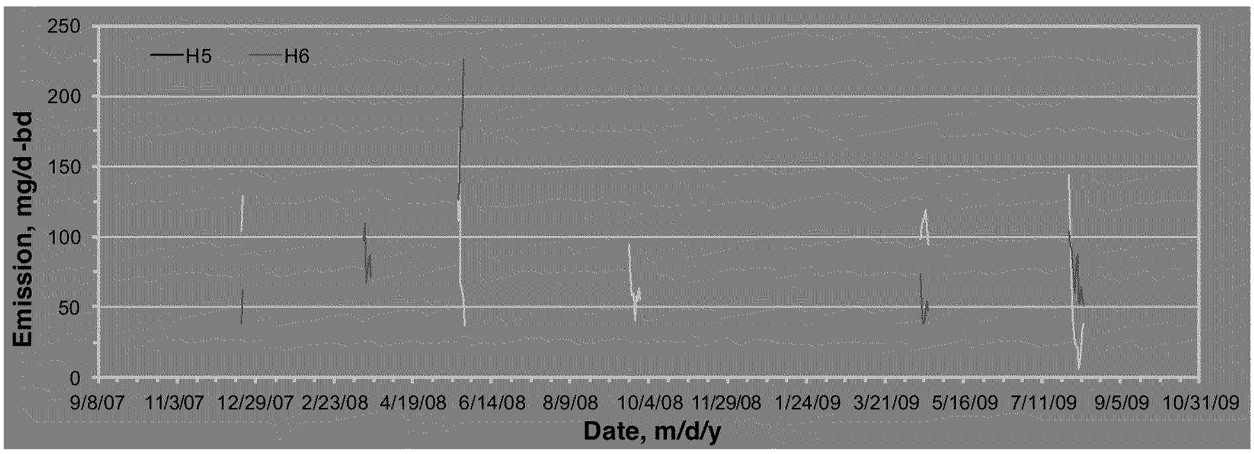


Figure 2.17. Daily mean hen-specific TSP emission rates.

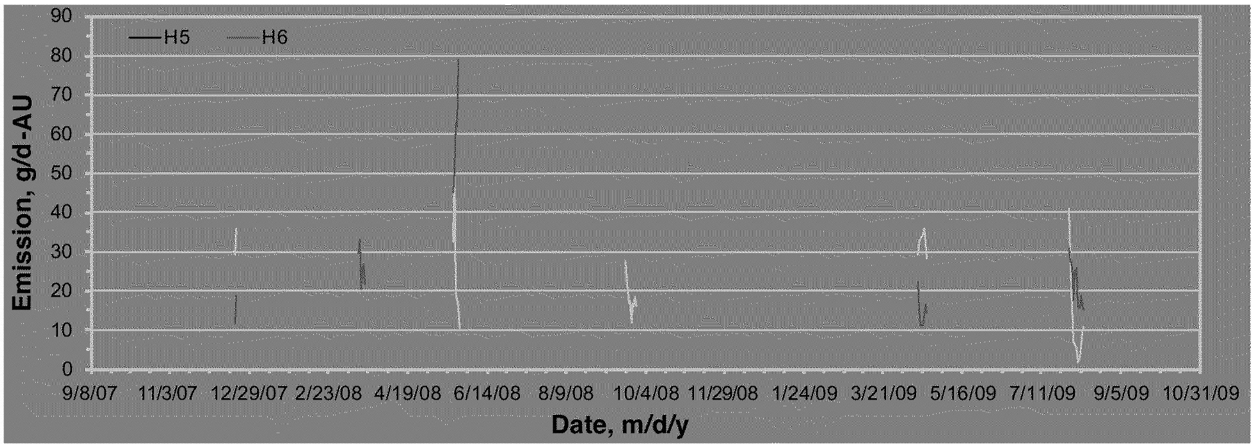


Figure 2.18. Daily mean LM-specific TSP emission rates.

2.4.4.2. PM_{10} Concentration and Emission

The PM_{10} measurements were collected continuously from the inlet to one of the continuously operating minimum fans in each house, as well as above the roof of the on-farm instrument shelter, with the exception of TSP and $PM_{2.5}$ monitoring periods. The characteristics of the concentrations are displayed in Table 2-82.8 and Figure 2.19. The ADM PM_{10} concentrations in H5 and H6 were 52 and 35% of the ADM TSP concentrations in H5 and H6, respectively. The ADM inlet PM_{10} and TSP concentrations were within 2 μg dsm^{-3}. This similarity suggests the majority of the inlet PM was respirable (<10 μm).

Table 2-8. Characteristics of inlet and exhaust PM_{10} concentrations (μg dsm^{-3}).

Variable	Inlet	House 5	House 6
Daily means			
Average	58	326	277
SD	47	157	163
n	556	490	547
Minimum	3	14	19
Maximum	363	1260	1130
Hourly means			
Average	58	325	276
SD	63	282	276
n	13718	12027	13574
Minimum	-17	-215	-251
Maximum	1045	5350	8124

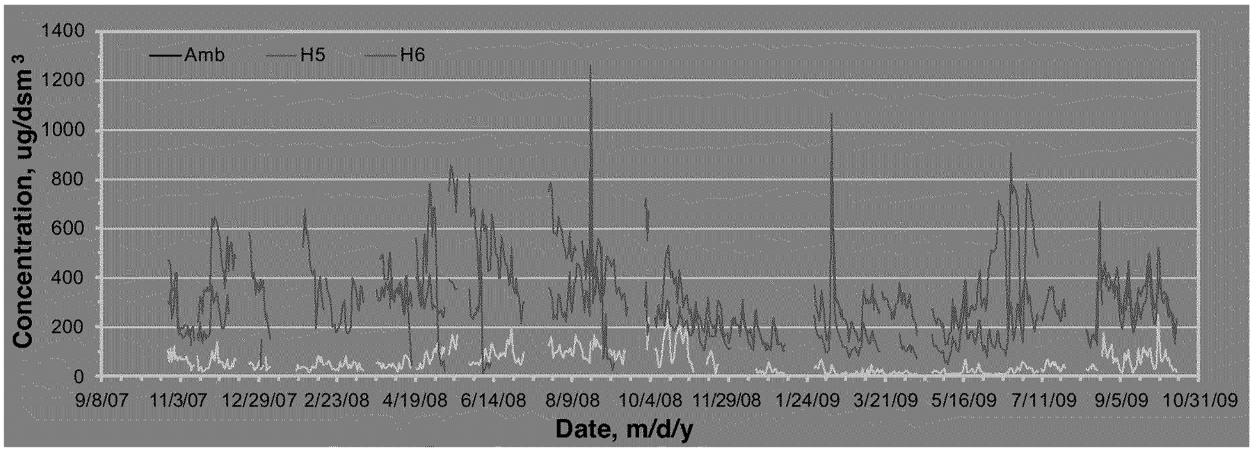


Figure 2.19. Daily mean PM_{10} concentrations.

The summary PM_{10} emission data are shown in Table 2-92.9 and Figure 2.20 to Figure 2.22. Summarized PM_{10} emission data from Roumeliotis and Van Heyst (2008) indicated a range from 2 to 10 g $d^{-1}AU^{-1}$ for a mechanically-ventilated high-rise house in Indiana; an Indiana battery cage system reported slightly higher PM_{10} emission rates of 15±3.4 g $d^{-1}AU^{-1}$. In this study, the LM-specific emission rates were approximately 10 g $d^{-1}AU^{-1}$. The results are comparable to literature values, and may be on the high end of reported ranges because of higher California temperatures.

Table 2-9. Average means±SD (n) of PM_{10} emission rates.

Variable	House 5	House 6
Daily mean emission rate		
House-specific, g d^{-1}	1273±1022 (451)	960±795 (527)
Area-specific, mg d^{-1} m^{-2}	653±524 (451)	492±408 (527)
Hen-specific, mg d^{-1} hd^{-1}	38±30 (451)	29±24 (524)
LM-specific, g $d^{-1}AU^{-1}$	11.5±9.8 (451)	9.45±8.42 (524)
Egg-specific, mg $d^{-1}doz^{-1}$	1691±8916 (423)	11824±55597 (525)
Hourly mean emission rate		
House-specific, g d^{-1}	1260±1760 (11159)	950±1377 (13141)
Area-specific, mg d^{-1} m^{-2}	646±903 (11159)	487±706 (13141)
Hen-specific, mg d^{-1} hd^{-1}	37±51 (11150)	29±41 (13063)
LM-specific, g $d^{-1}AU^{-1}$	11.3±15.8 (11150)	9.35±13.82 (13063)

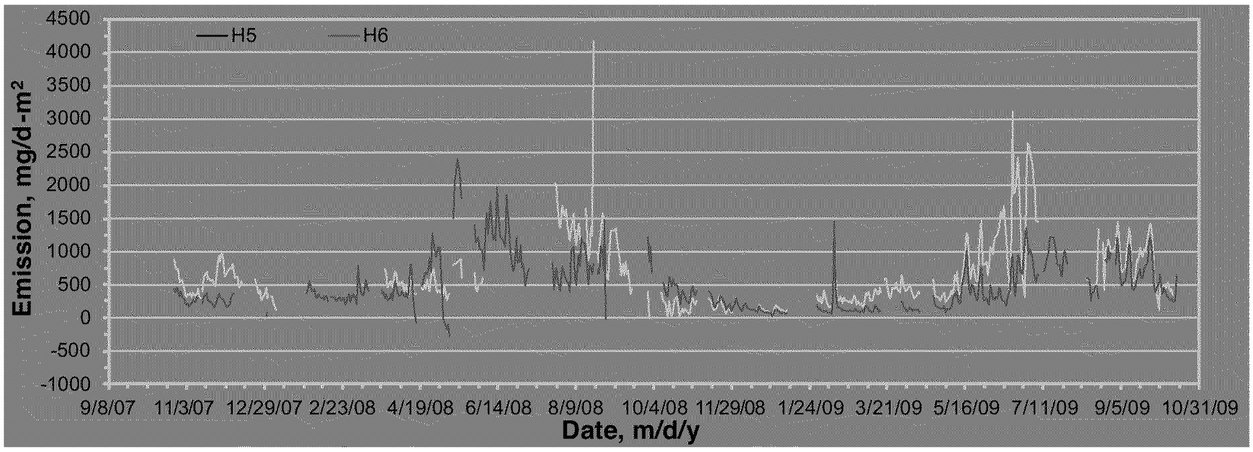


Figure 2.20. Daily mean area-specific PM_{10} emission rates.

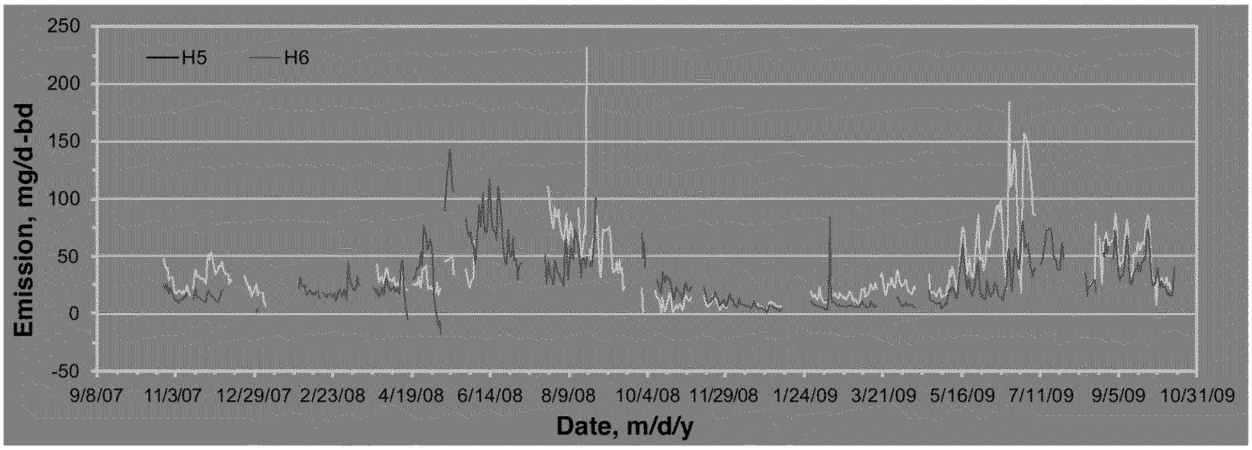


Figure 2.21. Daily mean hen-specific PM_{10} emission rates.

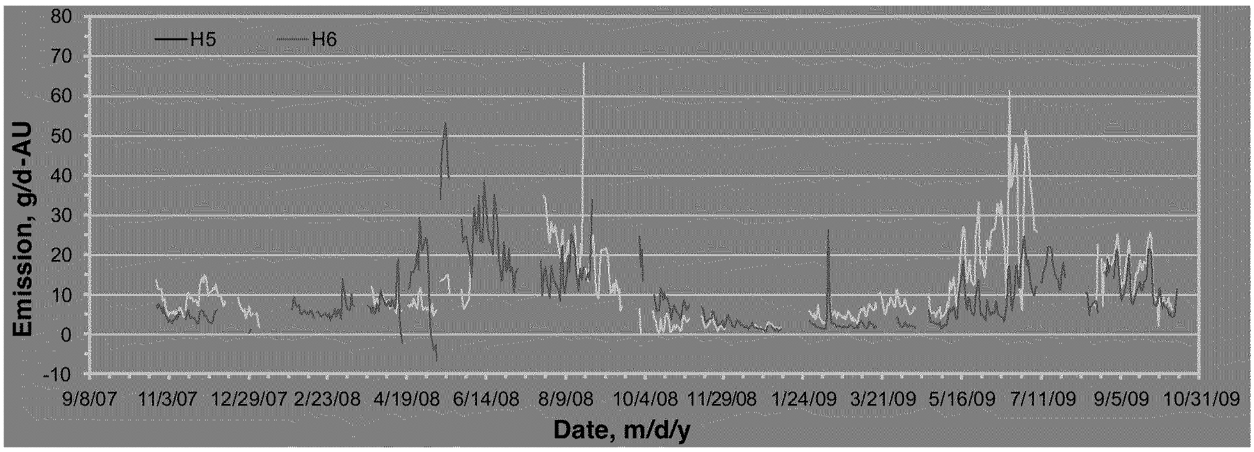


Figure 2.22. Daily mean LM-specific emission rates.

Summing the H5 and H6 ADM house-specific emissions and multiplying by four approximates the daily total emission, which translates to an annual emission from this pod of 3,260 kg (3.6 tons) per year.

A comparison of PM_{10} emission rates during non-molting and molting periods are shown in Figure 2.23. Higher PM_{10} emission rates were measured in H5 during molt compared with the active periods. This was expected because of feather loss during molt. However, the molting period measurements in H6 were half of the average for H5, and lower than the non-molting measurements for the same house.

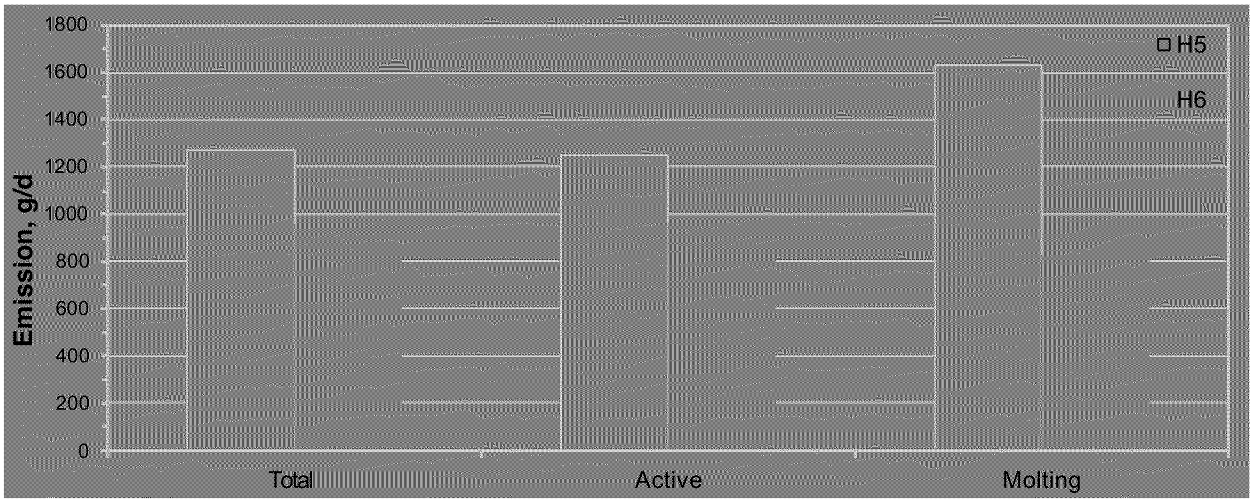


Figure 2.23. Comparison of house-specific emission rates during the total period, active periods, and molting periods.

The numbers of valid days of molting period measurements were 27 and 31 for H5 and H6, respectively. The majority of H5 molting period measurements were from May 2009, and the H6 measurements from March and April 2008. The difference in temperature and humidity during these two periods may explain the difference in molting period measurements between houses. Significant differences in several pollutants between houses were detected during the spring 2008 period when a molting period occurred in both H5 and H6.

The house differences that were thought to impact other pollutants likely also affected this analysis. The numbers of valid H5 and H6 active days were 421 and 491, respectively. The molting periods represented less than 7% of the total measurements, thus their influence on the total average PM_{10} emissions was negligible.

Based on a multiple variable analysis of variance of hourly, daily and weekly means, the impact of different factors and their interactions for full and active houses are displayed in Table 2-102.10 (only most significant factors listed for analysis of hourly means). The variables described in Table 2-102.10 suggest a very complex empirical model. The interaction between airflow and inlet temperature were the most significant predictor variables for daily and weekly mean emissions. Inlet temperature and hen activity were top factors for predicting hourly mean emissions. The house effect was significant in all cases.

Table 2-10. Parameters influencing area-specific PM_{10} emission.

Hourly Means		Daily and Weekly Means	
Parameter	**R^2**	**Parameter**	**R^2**
Inlet Temp * Solar	0.401	**Daily Means**	
Solar * Hen Activity	0.471	Inlet Temp * Ventilation	0.423
Inlet Temp * Hen Activity	0.512	LMD * Days of Manure	0.436
Solar * Static Pressure	0.548	Hen Age * Ventilation	0.457
Time of Day * Solar	0.562	House	0.487
House	0.573	LMD * Hen Age	0.509
Inlet Temp * Inlet RH	0.583	Exhaust Temp	0.514
Inlet Temp * Exhaust RH	0.592	LMD * Exhaust Temp	0.515
Time of Day * Inlet Temp	0.600	Inlet Temp * Exhaust Temp	0.516
Exhaust Temp * LMD	0.602	Hen Age * Exhaust Temp	0.517
Inlet RH * Solar	0.605		
Solar * Hen Age	0.607		
Hen Activity * Hen Age	0.612	**Weekly Means**	
Solar	0.616	Inlet Temp * Ventilation	0.578
Solar * LMD	0.619	House	0.623
Inlet Temp * Hen Age	0.621	Eggs* Manure age	0.674
Exhaust RH * Hen Activity	0.624	Water * Hen Age	0.725
Inlet RH * Hen Activity	0.628	Inlet Temp * Hen Age	0.752
Ventilation * Solar	0.630	Water * Manure age	0.767
Time of Day * Hen Age	0.632	Hen Age * Manure age	0.776
Exhaust Temp * Atmospheric Pressure	0.633	Egg s* LMD	0.784
Exhaust RH * Static Pressure	0.644	Manure age	0.791
Exhaust RH * Hen Age	0.651	Ventilation * LMD	0.799
LMD * Hen Age	0.655	Exhaust Temp * Manure age	0.803
Exhaust Temp * Inlet RH	0.658	Exhaust Temp * Hen Age	0.812
Inlet Temp * Static Pressure	0.660	LMD * Hen Age	0.817
Ventilation * Inlet RH	0.664	Water	0.828
Time of Day * Ventilation	0.666	Inlet Temp * Manure age	0.834
Inlet RH * Exhaust RH	0.667		
Time of Day * Exhaust Temp	0.669		
Time of Day * Exhaust RH	0.670		
Time of Day * Inlet RH	0.671		
Ventilation * Inlet Temp	0.672		

The main sources of PM production in a layer house are feathers, feed and litter. Emission prediction equations based on exhaust temperature and live mass density, for hourly, daily and weekly means are shown in equations 2.1-2.3, respectively.

Hourly: $E = -2174 + 18.43\ D + 97.13\ T,\quad R^2 = 0.25 \qquad (2.1)$
Daily: $E = -957 - 10.02\ D + 81.67\ T,\quad R^2 = 0.36 \qquad (2.2)$
Weekly: $E = -1430 + 87.96\ T,\quad R^2 = 0.46 \qquad (2.3)$

Where E = PM_{10} emission, mg d^{-1} m^{-2};
T = Exhaust temperature, °C; and
D = Live mass density, kg m^{-2}.

Single variable regression was also performed between hourly PM_{10} emission averages and key factors are shown in Table 2-112.11. Particulate matter emission showed strong relationships (R>0.4) to environmental parameters including ventilation rate, inlet and exhaust temperatures, solar radiation, and inlet RH. Graphical depictions of these relationships for H5 are shown in Figure 2.24; similar patterns were observed for H6.

Table 2-11. Correlations between area-specific PM_{10} emission and various factors.

Parameter	Averaging Interval	r
Ventilation	Weekly	0.751
Inlet temp	Weekly	0.707
Exhaust temp	Weekly	0.680
Ventilation rate	Daily	0.638
Inlet temperature	Daily	0.620
Exhaust temperature	Daily	0.596
Exhaust temperature	Hourly	0.568
Solar radiation	Hourly	0.541
Ventilation rate	Hourly	0.525
Inlet temperature	Hourly	0.500
Hen age	Weekly	0.274
Hen age	Daily	0.244
Wind speed	Hourly	0.138
Hen activity	Hourly	0.129
Water consumption	Weekly	0.107*
Time of day	Hourly	0.034
Static pressure	Hourly	-0.004*
Manure age	Daily	-0.023*
Manure age	Weekly	-0.075*
Feed	Weekly	-0.190
Atmosphere pressure	Hourly	-0.191
Live mass density	Weekly	-0.237
Exhaust relative humidity	Hourly	-0.230
Live mass density	Daily	-0.269
Inlet relative humidity	Hourly	-0.481

Note: Observations ranged from 16446-18278, 862-866, and 112-174 for hourly, daily and weekly means, respectively. * = p>0.01.

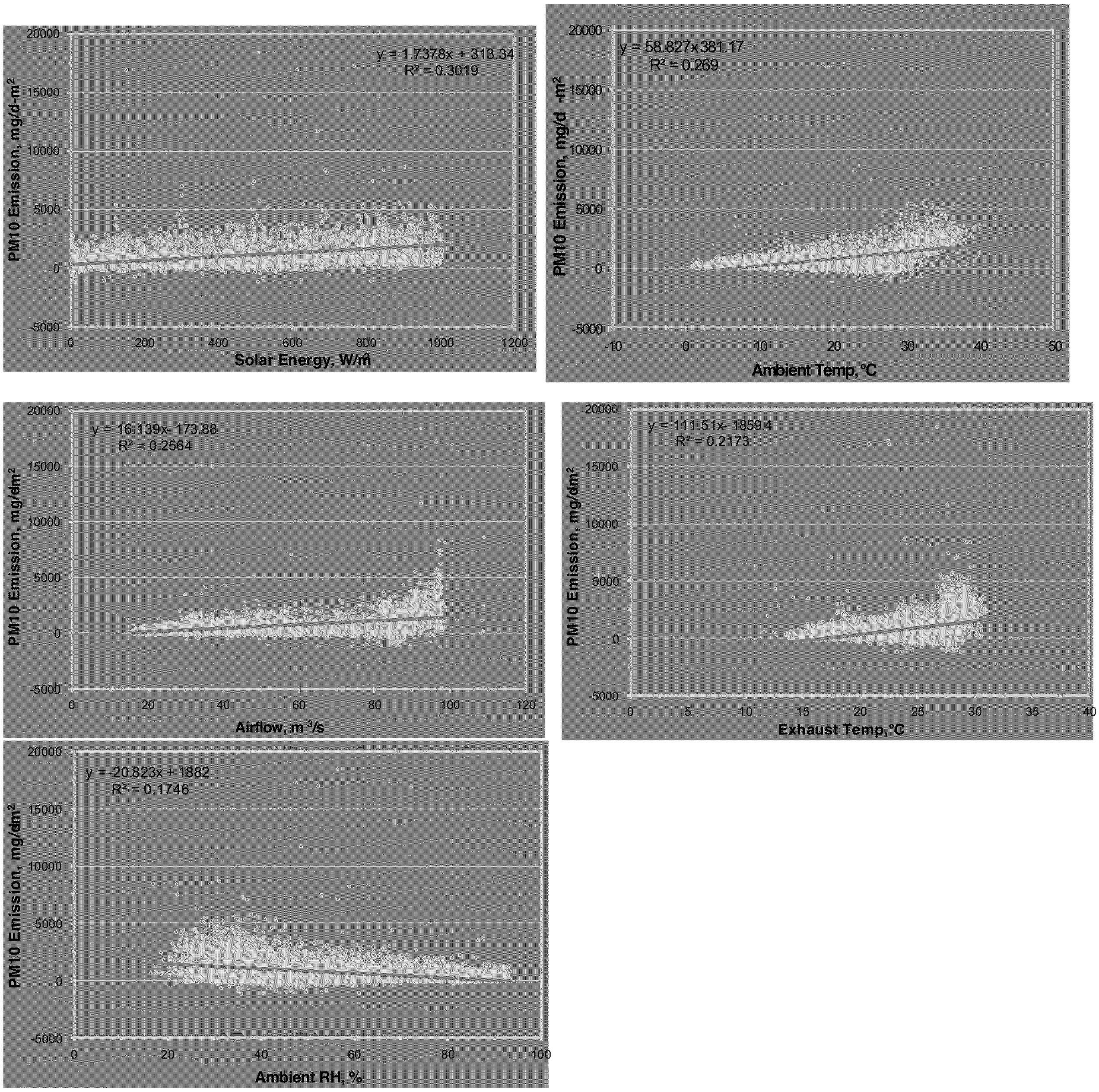


Figure 2.24. Correlations between area-specific hourly PM_{10} emission and solar energy (a), inlet temperature (b), airflow (c), exhaust temperature (d) and inlet RH (e) for H5.

2.4.4.3. $PM_{2.5}$ Concentration and Emission

The $PM_{2.5}$ measurements were collected during three periods totaling up to 47 d for both house and inlet conditions (Table 2-122.12 and Figure 2.25). The ADM $PM_{2.5}$ concentrations in H5 and H6 were 20 and 15% of the ADM PM_{10} concentrations in H5 and H6, respectively. A graphical comparison of the ADM inlet concentrations, based on particle size, is shown in Figure 2.26.

Table 2-12. Characteristics of inlet and exhaust $PM_{2.5}$ concentrations┐ (µg┐$^{-3}$). dsm

Variable	Inlet	House 1	House 2
Daily means			
Average	29	65	43
SD	23	91	63
n	32	47	45
Minimum	1	-4	-47
Maximum	112	337	237
Hourly means			
Average	29	66	40
SD	30	125	106
n	795	1180	1163
Minimum	-10	-12	-625
Maximum	232	706	641

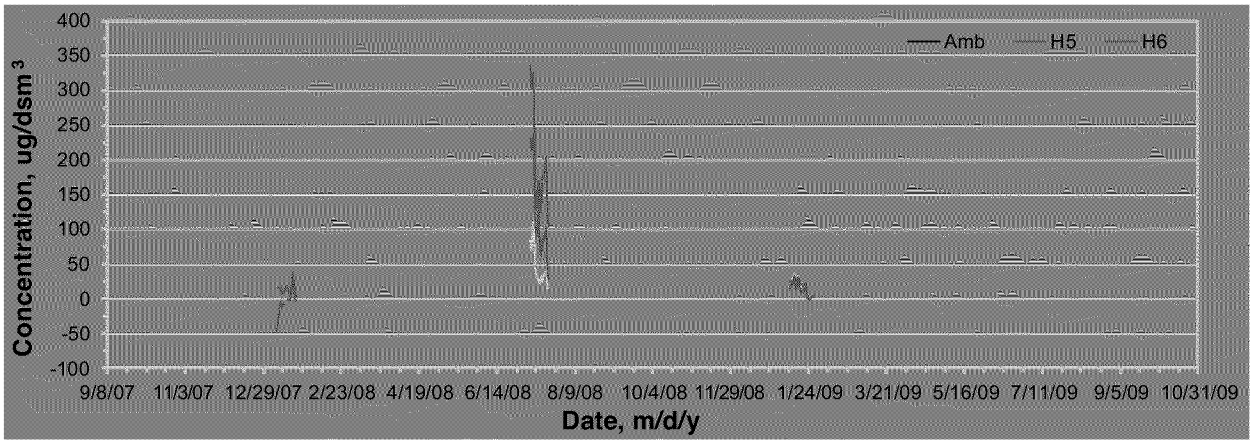


Figure 2.25. Daily mean $PM_{2.5}$ concentrations.

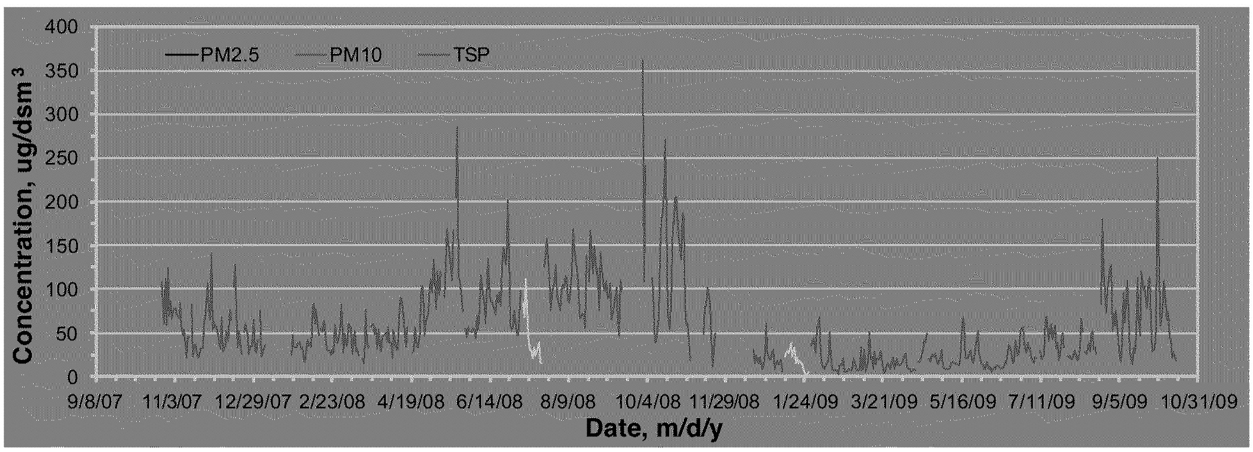


Figure 2.26. Daily mean concentrations of all three measured PM fractions in the inlet (ambient) air.

The summary $PM_{2.5}$ emission data are shown in Table 2-132.13, and Figure 2.27 to Figure 2.29. The literature data on $PM_{2.5}$ emissions from mechanically-ventilated high-rise buildings is very limited. For a battery-cage layer house, Lim et al. (2003) reported 1.1±0.3 g $d^{-1}AU^{-1}$, very similar to this study.

Table 2-13. Average means±SD (n) of $PM_{2.5}$ emission rates.

Variable	House 5	House 6
Daily mean emission rate		
House-specific, g d^{-1}	238±531 (40)	168±338 (43)
Area-specific, mg d^{-1} m^{-2}	122±272 (40)	86±173 (43)
Hen-specific, mg d^{-1} hd^{-1}	7±15 (40)	5±10 (43)
LM-specific, g $d^{-1}AU^{-1}$	2.33±5.19 (40)	1.96±3.83 (43)
Egg-specific, mg d^{-1} doz^{-1}	273±5418 (40)	71±142 (43)
Hourly mean emission rate		
House-specific, g d^{-1}	241±749 (1017)	155±603 (1124)
Area-specific, mg d^{-1} m^{-2}	123±384 (1017)	80±309 (1124)
Hen-specific, mg d^{-1} hd^{-1}	7±21 (1017)	5±18 (1124)
LM-specific, g $d^{-1}AU^{-1}$	2.36±7.32 (1017)	1.84±6.84 (1124)

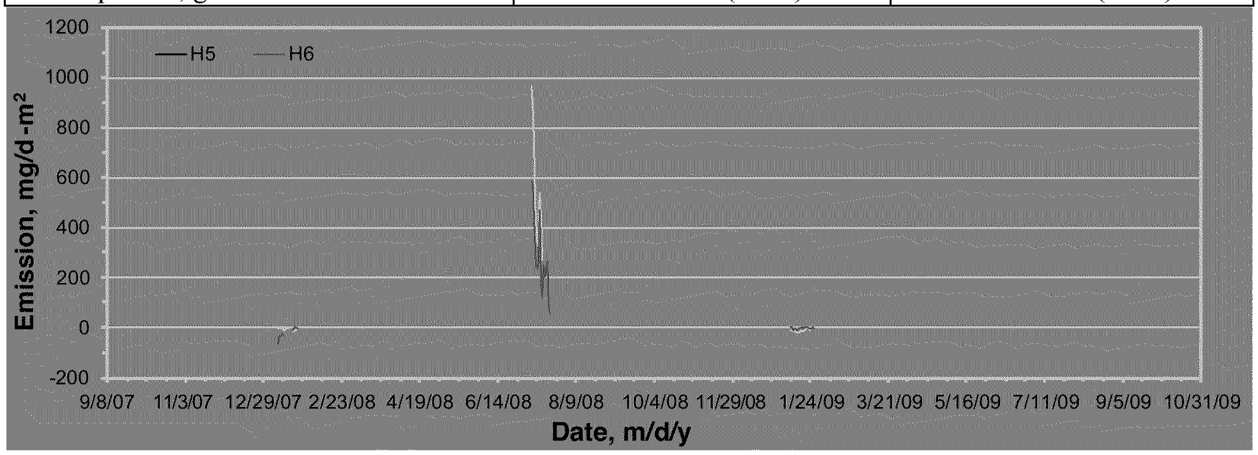


Figure 2.27. Daily mean area-specific $PM_{2.5}$ emission rates.

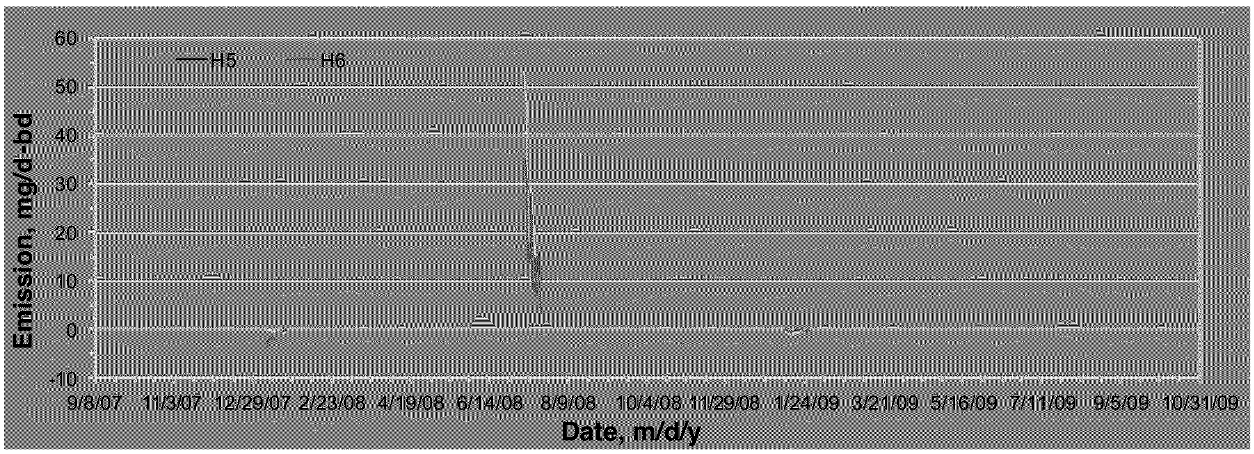


Figure 2.28. Daily mean hen-specific $PM_{2.5}$ emission rates.

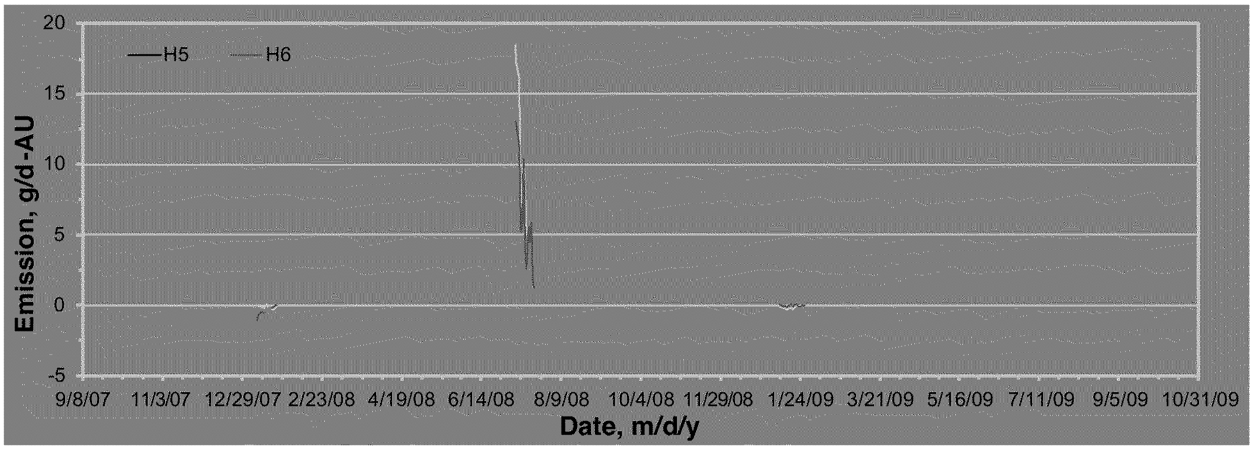


Figure 2.29. Daily mean LM-specific $PM_{2.5}$ emission rates.

2.4.5. VOC Concentration and Emission

The typical concentrations of total VOC in house exhaust air ranged from a low of approximately 0.28 mg m^{-3} (house 5 sample in mid-October) to a high of 1.13 mg m^{-3} (house 5 sample in mid-June). However, the concentrations of the samples from 10/2/09 were an order of magnitude higher than the rest of the samples; the concentrations ranged from 9.58 to 11.4 mg m^{-3}. Explanations for these high concentration measurements, including sampling error or contamination, temporary addition of DDGS to feed, insecticide/fungicides, etc., were sought, but no conclusive cause for data error was determined. The mean emissions calculated without the 10/2/09 outliers were 3.31 and 2.13 kg/d for houses 5 and 6, respectively.

Single-factor correlation analyses were conducted for the daily VOC emission rates (Table 2-142.14). For both houses, this analysis was conducted with and without the 10/2/09 data included in the dataset. Temperature, airflow and solar factors tended to have stronger positive relationships with the VOC emission rates, and relative humidity, wind speed and hen weight showed inverse relationships, for the reduced data sets.

Because the VOC sampling dates were limited to a maximum of 7 d in 2009, there is potential for significant bias when extrapolating the average results to an annual average. To assess whether potentially important environmental parameters during VOC sampling were representative of the two-year averages, they were compared in Table 2-152.15.
The average inlet temperatures during sampling periods were up to 4ºC higher than the 2-yr average, but the difference in house exhaust temperatures were less dramatic as a result of the constant setpoint temperature used in the houses throughout the year. The house airflow during VOC sampling was also higher, likely a result of the sampling occurring in late summer and fall. House temperature and airflow showed a strong correlation with VOC emission in the H5 (with the 10/2/09 sample removed) dataset only (Table 2-142.14), thus, the calculated VOC emissions factors probably need some adjustment to account for bias introduced by sampling time.

Table 2-14. Correlation coefficients (r) between daily VOC emission and various factors.

House 5 (n=6)		House 6 (n=5)		House 5 (w/o 10/2 sample, n=5)		House 6 (w/o 10/2 sample, n=4)	
House dP	0.628	Airflow	0.184	Inlet T	0.913	Solar	0.998
Hen Wt	0.156	House dP	0.142	Exhaust Temp	0.785	Inventory	0.905
Airflow	0.152	Inlet T	0.089	Airflow	0.755	dP	0.761
LMD	0.144	Hen Wt	0.007	Solar	0.747	Inlet T	0.667
Inlet T	0.021	Solar	-0.007	Inventory	0.699	Airflow	0.580
Solar	-0.022	LMD	-0.027	House dP	0.116	Exhaust Temp	0.513
Exhaust Temp	-0.089	Inventory	-0.033	House RH	0.097	LMD	0.478
Inventory	-0.195	Exhaust Temp	-0.152	LMD	-0.345	Atm Pressure	0.095
Atm Pressure	-0.288	Atm Pressure	-0.336	Hen Wt	-0.407	Exhaust RH	0.043
Wind Speed	-0.606	Wind Speed	-0.642	Atm Pressure	-0.428	Inlet RH	-0.492
House RH	-0.776	House RH	-0.823	Wind Speed	-0.608	Hen Wt	-0.531
Inlet RH	-0.796	Inlet RH	-0.877	Inlet RH	-0.810	Wind Speed	-0.572

House temperature was correlated with VOC emission, thus, calculated VOC emissions factors need some adjustment to account for bias introduced by the time of sampling to best estimate annual emissions from a limited data set. A linear regression of VOC emission (V) and inlet temperature (T) without the outlier results in V = 0.31 T – 2.8 (R^2=0.52) for house 5. The regression was insignificant for house 6 so no adjustment was made to the measured average. Using the house 5 equation to predict the annual average VOC emission based on the historical mean inlet temperature of 17.0°C results in V = 0.31 (17.0°C) – 2.8 = 2.49 kg/d. The hen-specific emission at this rate would be 76.0 mg/d-hen. The average of both houses was 71.3 mg/d-hen. At this rate, it would require about 3.9 million hens to emit 100 tpy and 9.7 million hens to emit 250 tpy.

Table 2-15. Averages of influencing factors during VOC sampling events and the NAEMS.

Variable	House 5		House 6	
	Sampling	2-year	Sampling	2-year
Inlet T, ºC	21.7	17.8	20.6	17.8
Indoor T, ºC	24.6	22.3	24.0	22.3
Solar, W m^{-2}	243	213	221	213
Inventory, hd	32614	33073	32107	32124
Ave Wt, kg	1.63	1.61	1.68	1.54
Density, kg m^{-2}	27.3	28.2	27.7	26.2
Airflow, m^3 s^{-1}	57.6	47.6	50.8	46.0

2.4.6. Hydrogen Sulfide Concentration and Emission

Table 2-162.16 and Figure 2.30 show the characteristics of the hydrogen sulfide (H_2S) concentration measurements. The ADM (±SD) inlet concentration was 2±2 ppb.

The ADM (±SD) concentrations in B1 and B2 were 11±6 and 13±12 ppb, respectively. Even at the maximum AHM exhaust concentration of 93 ppb, the house environment was well below the recommended 8-hr occupational exposure limit of 10 ppm (NIOSH 2005).

Table 2-16. Characteristics of inlet and exhaust H_2S concentrations (ppb).

Variable	Inlet	House 1	House 2
Daily means			
Average	2	11	13
SD	2	6	12
n	703	691	682
Minimum	0	1	1
Maximum	11	39	70
Hourly means			
Average	2	11	13
SD	2	7	13
n	16919	16743	16590
Minimum	-1	0	0
Maximum	24	71	93

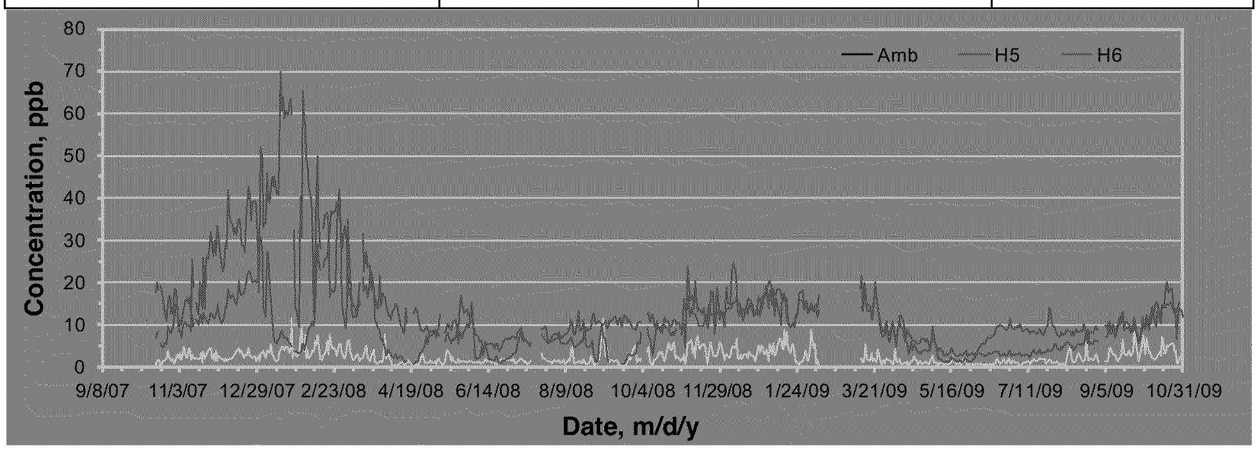


Figure 2.30. Daily mean hydrogen sulfide concentrations.

Table 2-172.17 and Figure 2.31 to Figure 2.33 show the mean H_2S emission rates on area, hen, live mass and egg-specific bases.

Table 2-17. Average means±SD (n) of H_2S emission rates.

Variable	House 5	House 6
Daily mean emission rate		
House-specific, g d^{-1}	45.4±23.7 (614)	39.8±29.4 (633)
Area-specific, mg d^{-1} m^{-2}	23.3±12.1 (614)	20.4±15.1 (633)
Hen-specific, mg d^{-1} hd^{-1}	1.33±0.70 (614)	1.20±0.86 (632)
LM-specific, mg $d^{-1}AU^{-1}$	396±210 (614)	374±262 (632)
Egg-specific, mg d^{-1} doz^{-1}	88.7±572.4 (586)	79.9±405.1 (632)
Hourly mean emission rate		
House-specific, g d^{-1}	45.3±31.3 (15066)	39.9±33.2 (15494)
Area-specific, mg d^{-1} m^{-2}	23.2±16.1 (15066)	20.4±17 (15494)
Hen-specific, mg d^{-1} hd^{-1}	1.33±0.93 (15051)	1.2±0.98 (15459)
LM-specific, mg $d^{-1}AU^{-1}$	396±276 (15051)	375±300 (15459)

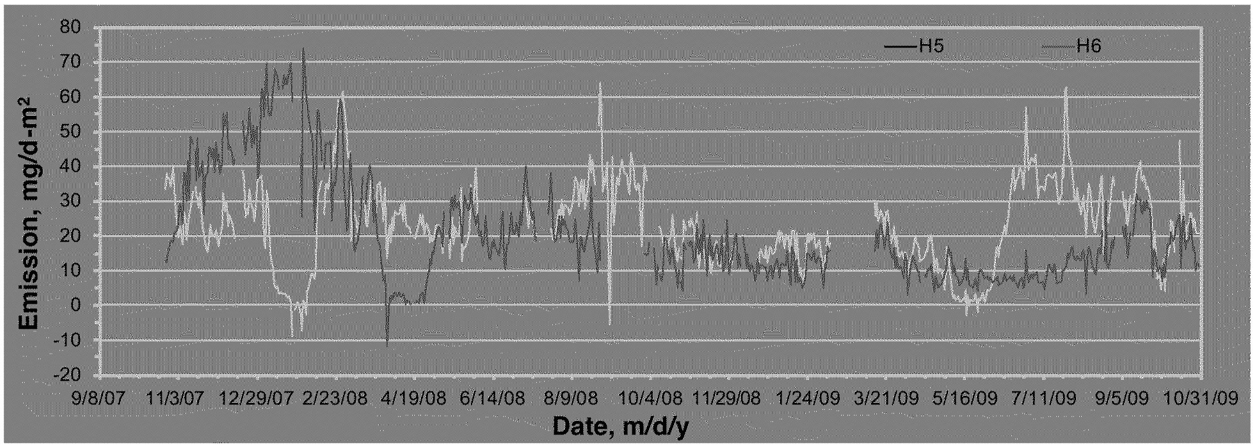


Figure 2.31. [redacted]

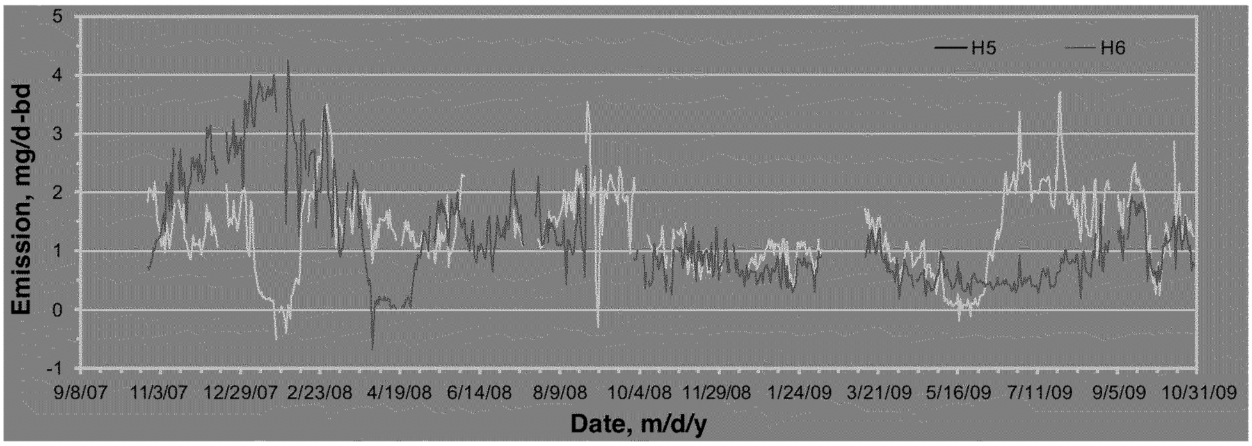


Figure 2.32. Daily mean hen-specific H_2S emission rates.

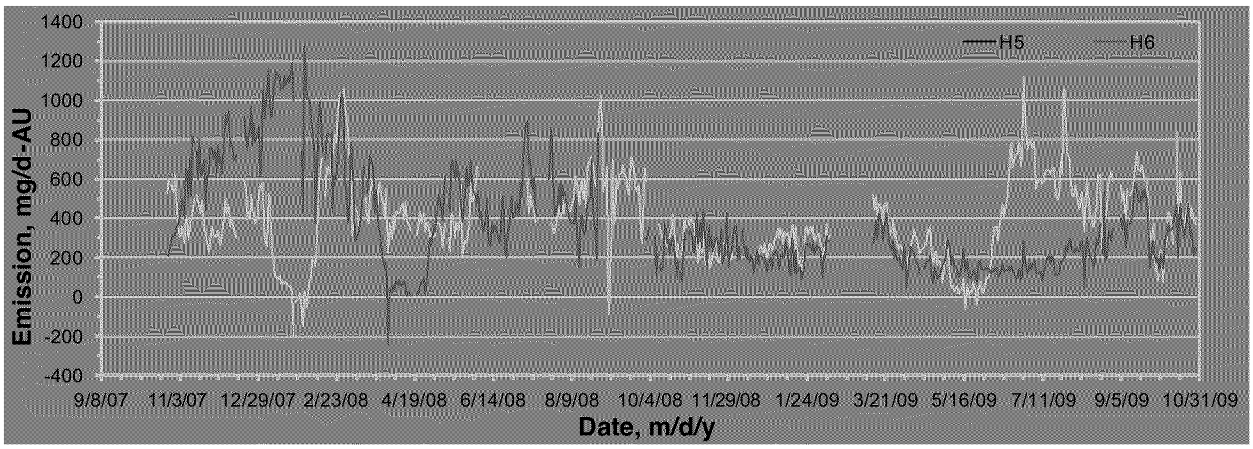


Figure 2.33. Daily mean LM-specific H_2S emission rates.

The H_2S emissions were impacted by the production period (Figure 2.34). The average house emission rates were 13 to 18% during molt compared with the non-molting (active) periods. The lower emission rates were likely related to reductions in fresh manure as influenced by reduced feed intake.

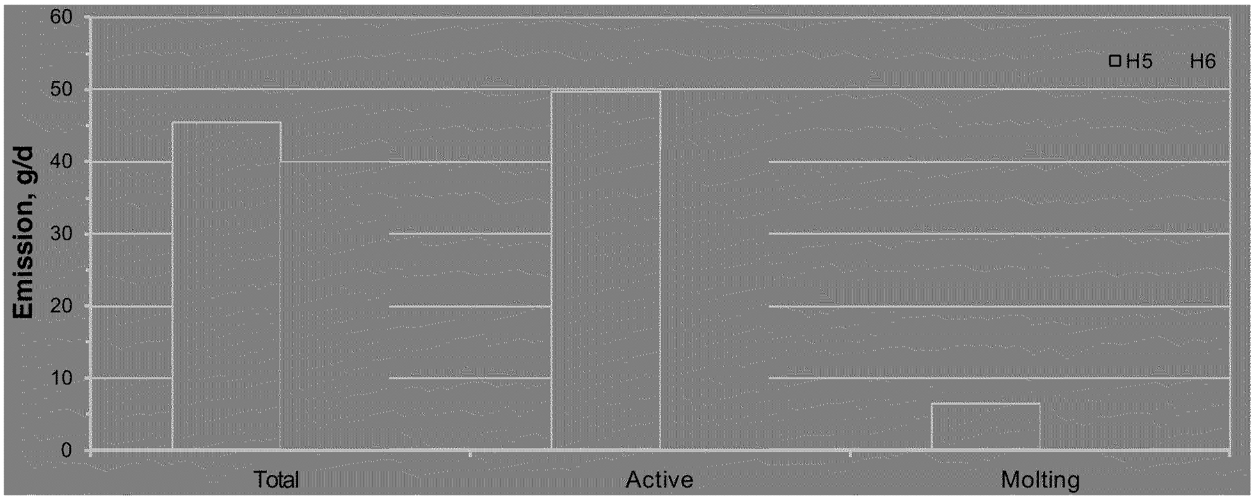


Figure 2.34. House-specific H_2S emission rates during overall, active, and molting periods.

Based on a multiple variable regression analysis, the impact of different factors and their interactions are displayed in Table 2-18. Clearly, hen activity (not included in daily or weekly means) and age dominated the prediction of hourly means while manure age (not included in hourly means), water consumption, hen age, and outside (inlet) temperature were important correlators with daily and weekly means. The main H_2S production site in a layer house is the litter and anaerobic zones increase with manure age (time of accumulation in first floor).

Table 2-18. Parameters influencing area-specific H_2S emission.

Hourly Means		Daily and Weekly Means	
Parameter	**R^2**	**Parameter**	**R^2**
Hen Activity * Hen Age	0.299	**Daily Means**	
Static Pressure * Hen Activity	0.330	Manure Age	0.079
Exhaust RH * Hen Activity	0.389	Hen Age * Manure Age	0.171
Atmospheric Pressure * Hen Activity	0.394	Hen Age * Inlet Temp	0.266
Hen Activity	0.399	Inlet Temp * Ventilation	0.285
Static Pressure * Hen Age	0.405	Inlet Temp	0.357
Exhaust RH * Hen Age	0.409	Exhaust Temp * Ventilation	0.414
Inlet RH * Hen Age	0.430	Hen Age * Exhaust Temp	0.432
Inlet Temp * Hen Age	0.437	Hen Age * Ventilation	0.441
Inlet RH * Hen Activity	0.440	LMD * Inlet Temp	0.443
Ventilation * Hen Age	0.448	LMD * Hen Age	0.462
Inlet Temp	0.451		
Inlet RH * Exhaust RH	0.460		
Exhaust RH * Atmospheric Pressure	0.462	**Weekly Means**	
Atmospheric Pressure * Wind Velocity	0.465	Water * Manure Age	0.282
Ventilation * Inlet Temp	0.467	Inlet Temp * Ventilation	0.442
Hen Age	0.470	Feed * Manure Age	0.492
Ventilation	0.471	Eggs * Exhaust Temp	0.520
Atmospheric Pressure * Hen Age	0.475	House	0.558
Wind Velocity	0.476	Hen Age * Manure Age	0.573
Inlet Temp * Wind Velocity	0.477	Ventilation * Hen Age	0.599
Ventilation * Wind Velocity	0.478	Exhaust Temp * Ventilation	0.613
Inlet RH * Wind Velocity	0.479	Manure Age	0.615
Inlet Temp * Inlet RH	0.480	Eggs	0.621
Exhaust RH * Wind Velocity	0.482	Inlet Temp * Hen Age	0.633
Inlet Temp * Static Pressure	0.484	Exhaust Temp * Hen Age	0.637
Static Pressure	0.485	Eggs * Hen Age	0.676
Ventilation * Inlet RH	0.485	Inlet Temp * LMD	0.704
Ventilation * Exhaust RH	0.486	LMD * Hen Age	0.716
Inlet Temp * Exhaust RH	0.486	Feed * Ventilation	0.739
Exhaust RH * Static Pressure	0.486	Feed * Hen Age	0.743
Wind Velocity * Hen Activity	0.487	Water * Ventilation	0.749
Inlet Temp * Atmospheric Pressure	0.487		
Inlet RH * Static Pressure	0.488		
Ventilation * Atmospheric Pressure	0.488		
Atmospheric Pressure * Static Pressure	0.489		
Atmospheric Pressure	0.489		
Wind Velocity * Static Pressure	0.490		
Inlet RH	0.490		
Inlet Temp * Hen Activity	0.491		
Exhaust RH	0.491		
Inlet RH * Atmospheric Pressure	0.491		

Emission prediction equations based on exhaust temperature and live mass density, for hourly, daily and weekly means are shown in equations 2.4 to 2.6, respectively.

Hourly: $E = -33.3 + 1.591\ D + 0.478\ T$, $R^2 = 0.040$ (2.4)
Daily: $E = -7.98 + 1.097\ D$, $R^2 = 0.031$ (2.5)
Weekly: $E = -8.542 + 1.113\ D$, $R^2 = 0.029$ (2.6)

Where E = H_2S emission, mg d^{-1} m^{-2};
T = Exhaust temperature, °C; and
D = Live mass density, kg m^{-2}.

Single variable regression was performed between hourly and daily average H_2S emission rates and key factors are shown in Table 2-192.19Table 2-192.19. Water consumption, live mass density, hen age, solar radiation, ventilation rate and inlet and exhaust temperatures were the most significant positive influences on H_2S emission, whereas house static pressure and manure age were the most significant inverse influences. There were no correlation coefficients greater than 0.4.

Table 2-19. Correlation coefficients (r) between area-specific H2S emission and various factors (* = p>0.05).

Parameter	Averaging interval	r
Water consumption	Weekly	0.378
LMD	Daily	0.342
Hen age	Weekly	0.257
Feed	Weekly	0.238
Solar radiation	Hourly	0.225
Ventilation rate	Hourly	0.209
Live mass density	Weekly	0.188
Inlet temperature	Hourly	0.185
Exhaust temperature	Hourly	0.173
Hen age	Daily	0.150
Egg production	Weekly	0.063*
Atmosphere pressure	Hourly	0.039
Exhaust relative humidity	Hourly	0.027
Time of day	Hourly	0.025
Wind speed	Hourly	0.005*
Ventilation	Daily	-0.009*
Ventilation	Weekly	-0.034*
Inlet relative humidity	Hourly	-0.036
Hen activity	Hourly	-0.062
Exhaust temperature	Daily	-0.075
Inlet temperature	Daily	-0.113
Exhaust temp	Weekly	-0.146*
Inlet temp	Weekly	-0.190
Static pressure	Hourly	-0.240
Manure age	Daily	-0.242
Manure age	Weekly	-0.333

Note: n = 22,148-24,119, 1235-1244, and 162-174 for hourly, daily and weekly means.

2.4.7. Ammonia Concentration and Emission

Table 2-212.21 and Figure 2.35 show the characteristics of the ammonia (NH_3) concentration measurements. The ADM (±SD) inlet concentration was 1.4±1.3 ppm.

The ADM (±SD) concentrations in B1 and B2 were 15.2±11.6 and 19.4±24.6 ppm, respectively. Cold-weather concentrations were considerably higher than summer concentrations, and ranged from 20 to 120 ppm. These concentrations were measured near the exhaust fans on the lower level where the manure was stored.

Table 2-20. Characteristics of inlet and exhaust NH_3 concentrations (ppm).

Variable	Inlet	House 1	House 2
Daily means			
Average	1.4	15.2	19.4
SD	1.3	11.6	24.6
n	670	662	654
Minimum	-0.3	0.5	0.5
Maximum	8.0	48.8	129
Hourly means			
Average	1.4	15.2	19.4
SD	1.5	12.4	26.4
N	16115	16045	15897
Minimum	-0.6	0.2	0.3
Maximum	10.3	68.5	168

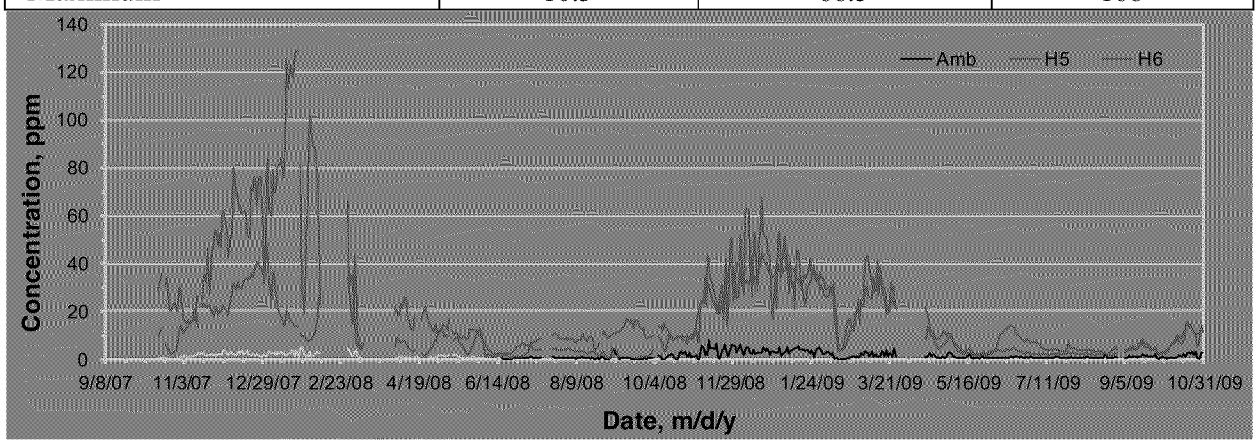


Figure 2.35. Daily means of ammonia concentrations.

Table 2-212.21 and Figure 2.36 to Figure 2.38 show the mean NH_3 emission rates on area, hen, live mass, AU and egg-specific bases. The Roumeliotis and Van Heyst (2008) review shows a range in NH_3 emissions from high-rise layer farms in Indiana from 200 to 500 g $d^{-1}AU^{-1}$. The ADM LM-specific emission rates fall within this range, being 282±139 and 293±255 g $d^{-1}AU^{-1}$ for H5 and H6, respectively. The unusually high SD for egg-specific emissions was due to many daily egg reports that combined egg production from the previous day with the current day.

Similar to H_2S, the NH_3 emissions were impacted by the production period. The average house emission rates were 31% to 34% during molt relative to the active periods. The lower emission rates are likely related to a reduction in fresh manure as influenced by reduced feed intake.

Summing the daily mean H5 and H6 emissions and multiplying by 4 approximates the daily total emission, which translates to an annual emission from this pod of 94,000 kg (104 tons) per year.

Table 2-21. Average means±SD (n) of NH_3 emission rates.

Variable	House 5	House 6
Daily mean emission rate		
House-specific, kg d^{-1}	32.7±17.2 (583)	31.7±29.5 (603)
Area-specific, g d^{-1} m^{-2}	16.7±8.8 (583)	16.2±15.1 (603)
Hen-specific, g d^{-1} hd^{-1}	0.95±0.49 (583)	0.94±0.86 (602)
LM-specific, g $d^{-1}AU^{-1}$	282±139 (583)	293±255 (602)
Egg-specific, g d^{-1} doz^{-1}	234±1149 (555)	112±514 (602)
Hourly mean emission rate		
House-specific, kg d^{-1}	32.6±21.6 (14314)	31.7±32.3 (14747)
Area-specific, g d^{-1} m^{-2}	16.7±11.1 (14314)	16.2±16.6 (14747)
Hen-specific, g d^{-1} hd^{-1}	0.95±0.62 (14299)	0.94±0.94 (14713)
LM-specific, g $d^{-1}AU^{-1}$	282±178 (14299)	292±282 (14713)

Ammonia emission was positively correlated most with atmospheric pressure and live mass density (r>0.4) and negatively correlated most with ventilation rate, and inlet and exhaust temperatures based on single variable regressions (Table 2-222.22). The strong inverse relationship with temperature in House 6 is evident in Figure 2.40. The inverse relationship with temperature is likely due to the effect of increased airflow drying the manure to such an extent that the negative effect of decreased moisture was greater than the positive effect of increased temperature. Reduced NH_3 emissions with dryer manure in the summer was also observed by Lim et al. (2004). The greater winter emissions produced higher correlations with atmospheric pressure and exhaust RH which are higher in the winter, even though they have no direct effect. Some positive correlation was observed with egg production and feed and water consumption. Some negative correlation was observed with hen age and manure age.

The impact of different factors and their interactions on a multiple variable regression analysis of selected potential factors are displayed in Table 2-232.23 and Table 2-24. Surprisingly, atmospheric pressure accounted for most of the variation in hourly means, but it was not included in the daily and weekly analysis. The most dominant direct effects were LMD, exhaust temperature, hen activity and house. Exhaust temperature was observed to be one of the top factors for all averaging intervals. Live mass density was the top flock characteristic, along with water consumption.

Emission prediction equations for hourly, daily and weekly means, based on exhaust temperature and live mass density are shown in equations 2.7 to 2.9, respectively.

Hourly: $E = -28.0 + 2.170\ D - 0.747\ T, \quad R^2 = 0.18$ (2.7)
Daily: $E = 15.9 + 1.377\ D - 1.681\ T, \quad R^2 = 0.34$ (2.8)
Weekly: $E = 36.8 + 1.102\ D - 2.266\ T, \quad R^2=0.46$ (2.9)

Where E = NH_3 emission, g d^{-1} m^{-2};
T = Exhaust temperature, °C; and
D = Live mass density, kg m^{-2}.

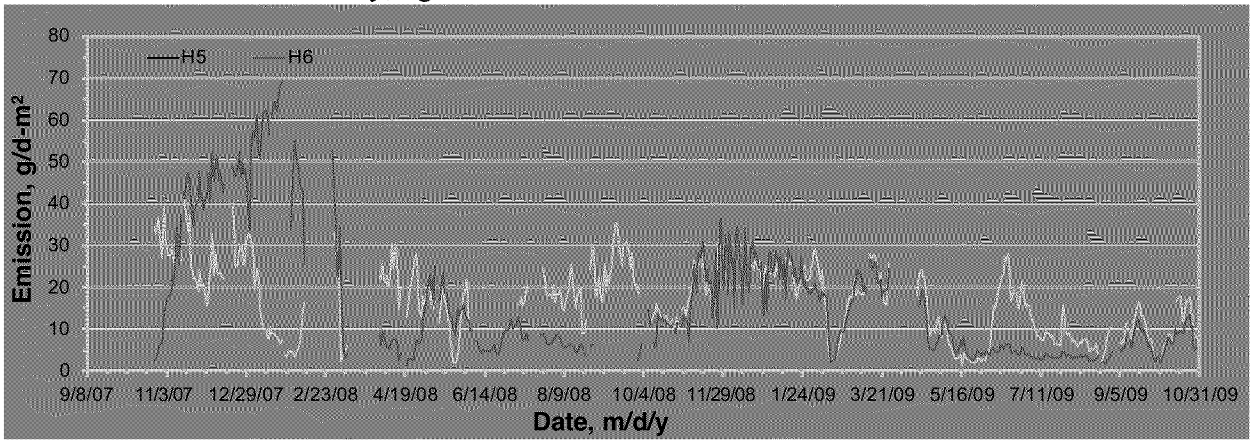


Figure 2.36. Daily mean area-specific NH_3 emission rates.

Table 2-22. Correlations between area-specific NH_3 emission and various factors (*p>0.05).

Parameter	Averaging interval	r
Atmosphere pressure	Hourly	0.507
Live mass density	Daily	0.450
Live mass density	Weekly	0.416
Egg production	Weekly	0.329
Exhaust relative humidity	Hourly	0.297
Inlet relative humidity	Hourly	0.254
Feed	Weekly	0.230
Hen activity	Hourly	0.138
Water	Weekly	0.113*
Time of day	Hourly	0.045
Static pressure	Hourly	-0.042
Solar radiation	Hourly	-0.096
Manure age	Daily	-0.188
Hen age	Weekly	-0.207*
Wind speed	Hourly	-0.215
Ventilation rate	Hourly	-0.220
Manure age	Weekly	-0.225
Hen age	Daily	-0.227
Exhaust temperature	Hourly	-0.317
Inlet temperature	Hourly	-0.329
Ventilation	Daily	-0.470
Exhaust temperature	Daily	-0.540
Ventilation	Weekly	-0.546
Inlet temperature	Daily	-0.557
Inlet temperature	Weekly	-0.648
Exhaust temperature	Weekly	-0.658

Note: n = 22,112-24,607, 1172-1183 and 143-151 for hourly, daily, and weekly, respectively.

The nominal N inputs and outputs to H5 and H6 combined, and relative to N intake via feed are shown in Figure 2.41. The aerial loss was 27% of the N intake via the feed. The result of the balance was 5% more N entering the house than leaving the house. The resulting balance is very sensitive to changes in feed, egg and manure N content, which were assessed once per balance period or once per study.

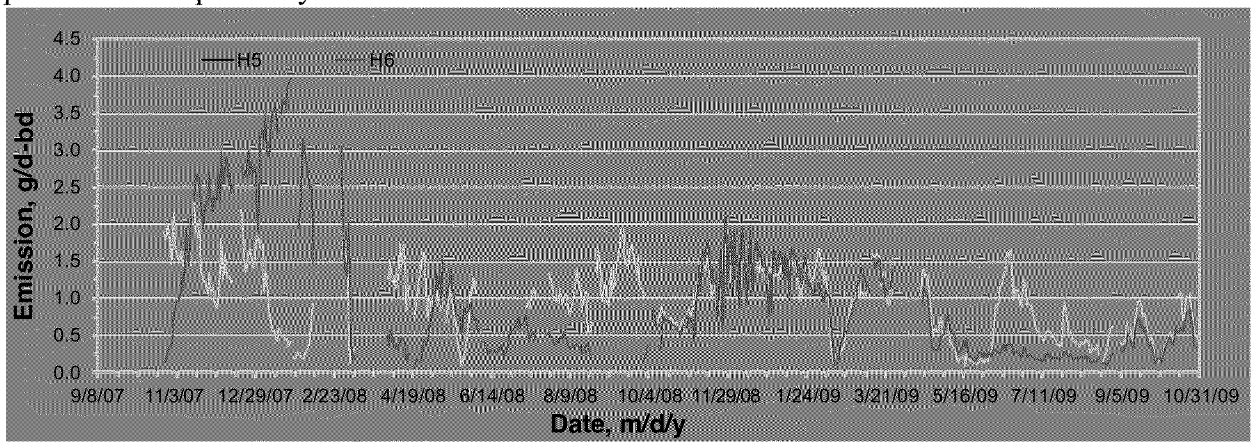


Figure 2.37. Daily mean hen-specific NH_3 emission rates.

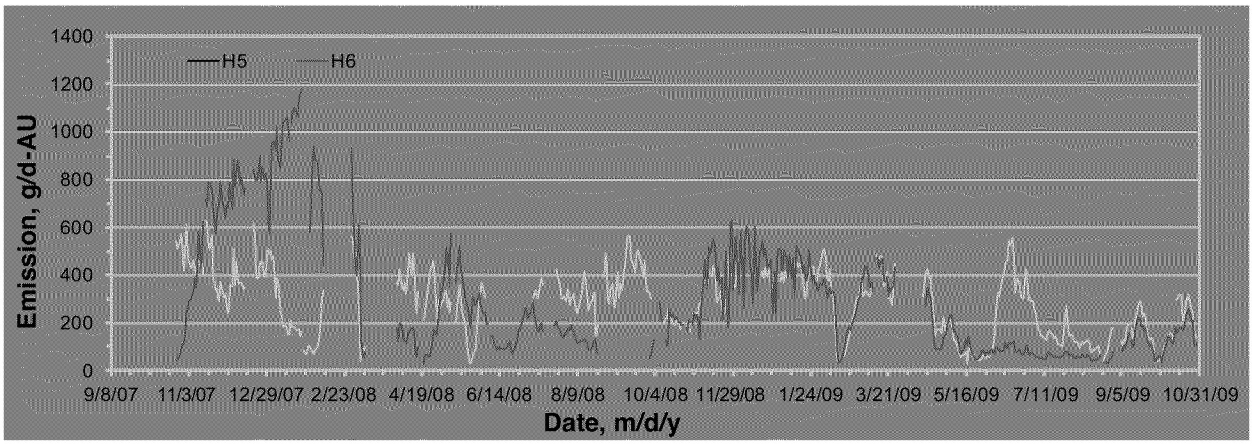


Figure 2.38. Daily mean LM-specific NH_3 emission rates.

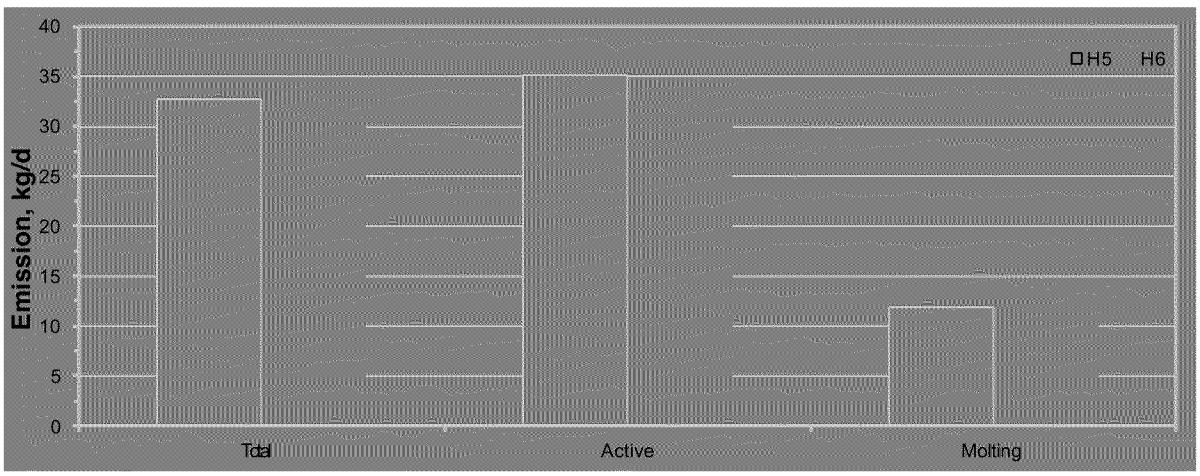


Figure 2.39. Comparison of house-specific NH_3 emission rates during total, active, and molting periods.

Table 2-23. Parameters influencing hourly mean area-specific NH_3 emission.

Parameter	R^2
Atmospheric Pressure	0.193
Exhaust RH * Static Pressure	0.321
Live Mass Density	0.369
Time of Day * Hen Activity	0.410
Exhaust Temp * Exhaust RH	0.456
Static Pressure * Hen Activity	0.532
House	0.539
Time of Day * Solar	0.546
Solar * Hen Activity	0.563
Atmospheric Pressure * Live Mass Density	0.571
Static Pressure	0.605
Time of Day * Exhaust Temp	0.610
Time of Day * Static Pressure	0.612
Static Pressure * Live Mass Density	0.613
Exhaust Temp * Hen Activity	0.617
Hen Activity * Live Mass Density	0.620
Exhaust RH * Atmospheric Pressure	0.621
Inlet Temp * Static Pressure	0.622
Exhaust Temp * Static Pressure	0.624
Inlet Temp * Atmospheric Pressure	0.627
Inlet Temp	0.629
Time of Day * Inlet Temp	0.629
Time of Day * Live Mass Density	0.631
Exhaust RH * Hen Activity	0.632
Exhaust RH * Solar	0.633
Atmospheric Pressure * Hen Age	0.635
Live Mass Density * Hen Age	0.637
Solar * Hen Age	0.641
Exhaust RH * Hen Age	0.642
Inlet Temp * Hen Age	0.644
Hen Activity * Hen Age	0.644
Inlet Temp * Wind Speed	0.645
Wind Speed * Hen Age	0.647
Static Pressure * Hen Age	0.648
Inlet Temp * Solar	0.648
Exhaust Temp * Solar	0.648
Solar * Wind Speed	0.649
Exhaust Temp * Wind Speed	0.649
Time of Day * Atmospheric Pressure	0.650
Time of Day	0.650
Exhaust Temp * Live Mass Density	0.650

Table 2-24. Parameters influencing daily and weekly mean area-specific NH_3 emissions.

Daily means		Weekly means	
Parameter	**R^2**	**Parameter**	**R^2**
Inlet Temp * Ventilation	0.379	Water Consumption	0.472
Live Mass Density * Exhaust Temp	0.407	Exhaust Temp * Inlet Temp	0.504
Manure Age * Ventilation	0.431	Inlet Temp * Ventilation	0.518
House	0.438	Water * Live Mass Density	0.529
Manure Age * Inlet Temp	0.442	Hen Age	0.585
Ventilation	0.454	Water * Hen Age	0.590
Live Mass Density * Manure Age	0.460	Exhaust Temp * Hen Age	0.608
Hen Age * Inlet Temp	0.464	Inlet Temp * Hen Age	0.621
Hen Age * Manure Age	0.490	Live Mass Density * Hen Age	0.626
Exhaust Temp * Ventilation	0.507	Egg production * Manure Age	0.633
Hen Age	0.515	Water * Manure Age	0.639
Live Mass Density * Hen Age	0.524	Live Mass Density * Manure Age	0.645
Hen Age * Ventilation	0.532	House	0.646
Manure Age * Exhaust Temp	0.536		
Manure Age	0.545		
Live Mass Density * Inlet Temp	0.546		
Hen Age * Exhaust Temp	0.547		

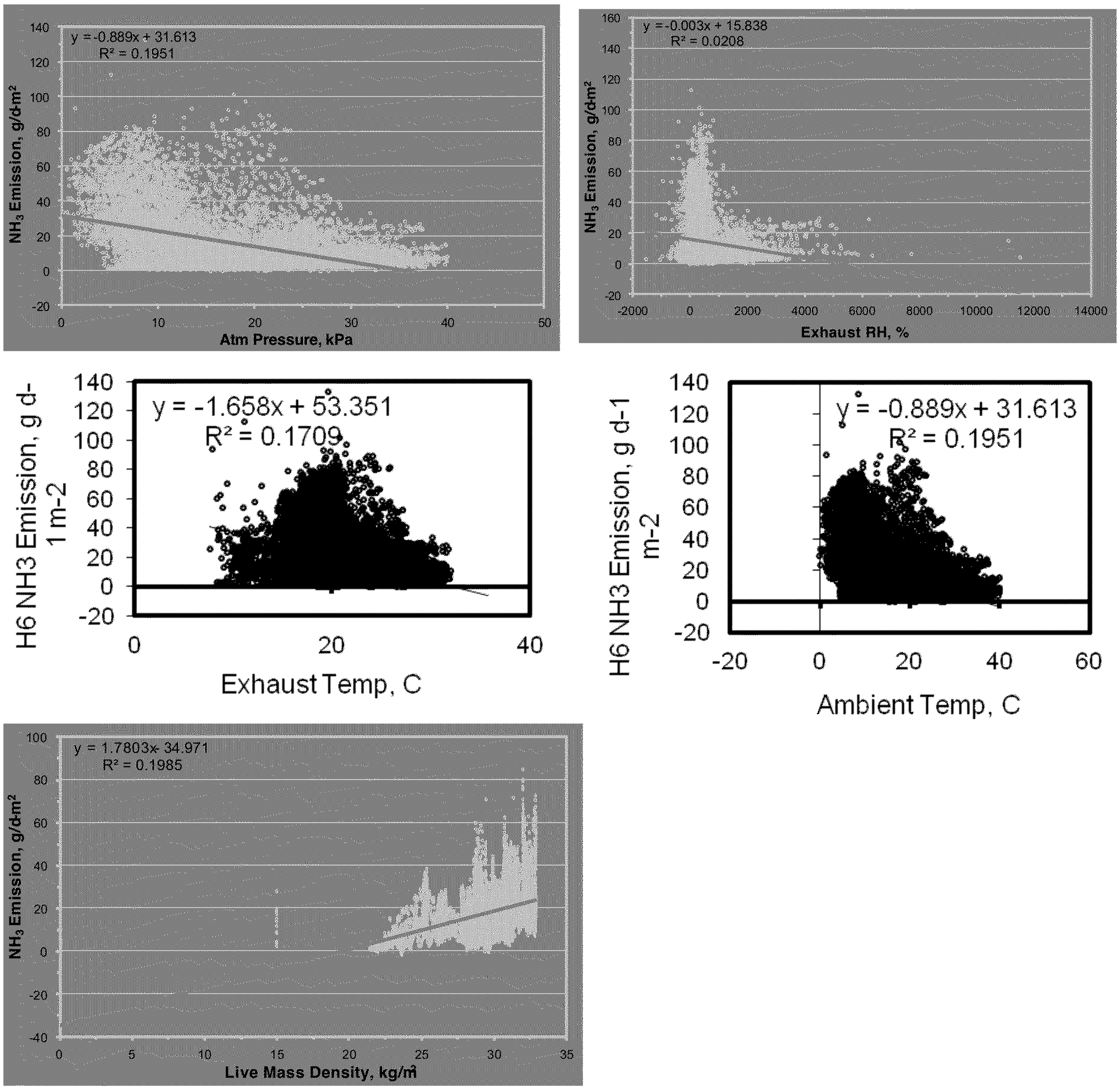
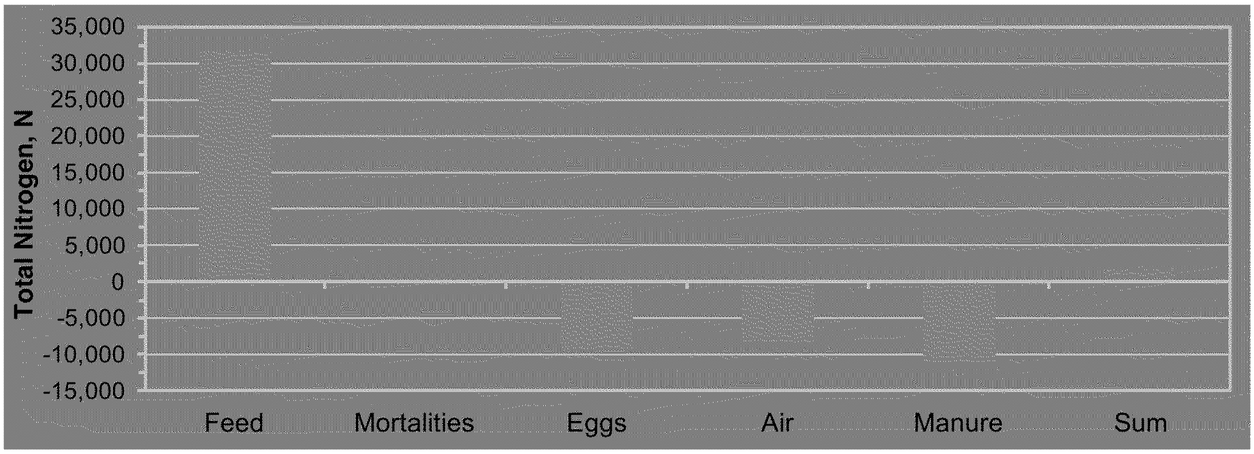
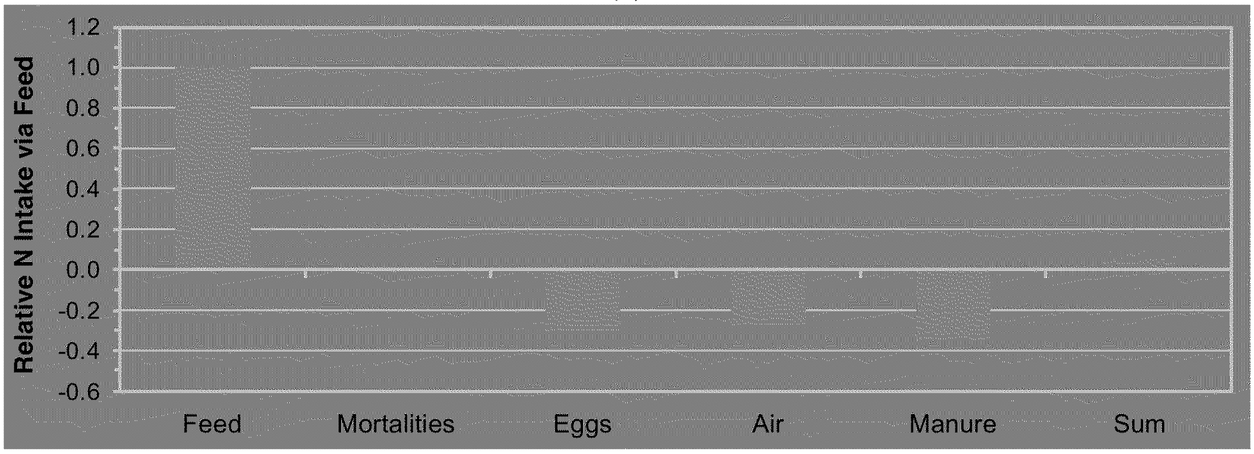


Figure 2.40. Correlations between area-specific hourly NH_3 emission rates and atmospheric pressure (a), exhaust relative humidity (b), exhaust temperature (c), inlet temperature (d), all for house 6, and live mass density (e), for H5.



(a)



(b)

Figure 2.41. The nitrogen (N) inputs and outputs to H5 and H6 combined, expressed in total N (a) and relative to N intake via the feed (b).

2.4.8. Carbon Dioxide Concentration and Emission

Table 2-252.25 and Figure 2.42 show the characteristics of the CO_2 concentration measurements. The ADM (±SD) inlet concentration was 474±50 ppm. This inlet concentration is higher than typical inlet measurements of 387 ppm (http://co2now.org/), but it is likely that some CO_2 exhausted from the sidewall fans circuited back through the inlet. This explanation highlights the need for representative inlet measurements to account for appropriate background pollutants.

The ADM (±SD) concentrations in B1 and B2 were 1024±314 and 1035±383 ppm, respectively. The cold-weather concentrations were considerably higher than in summer. The concentration patterns for both houses are considerably less variable compared with NH_3 and H_2S.

Table 2-25. Characteristics of inlet and exhaust CO_2 concentrations (ppm).

Variable	Inlet	House 1	House 2
Daily means			
Average	474	1024	1035
SD	50	314	383
n	672	662	654
Minimum	392	415	398
Maximum	660	1879	2256
Hourly means			
Average	474	1023	1034
SD	59	354	436
n	16168	16051	15900
Minimum	382	398	380
Maximum	781	2408	2712

Table 2-262.26 and Figure 2.43 to Figure 2.45 show the mean CO_2 emission rates on area, hen, live mass, and egg-specific bases. The CO_2 emission rates showed relatively lower variation than H_2S and CO_2, which suggests the hens were the dominant source of CO_2, and the variable manure contribution was lower. There was a drop in CO_2 emission during molting, relative to active periods (Figure 2.46). Li et al. (2005) estimated the CO_2 production of W-36 layer hens to range from 0.054 to 0.084 kg/d-hen depending on the amount of light. The hen-specific ADM (Table 2-262.26) suggests there was some CO_2 production by the manure, especially in H5.

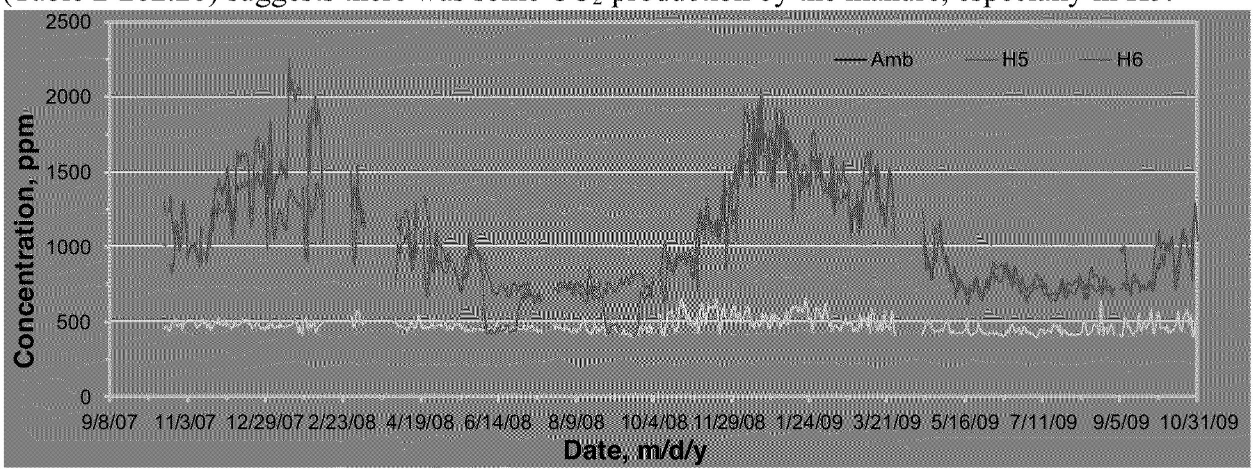


Figure 2.42. Daily mean CO_2 concentrations.

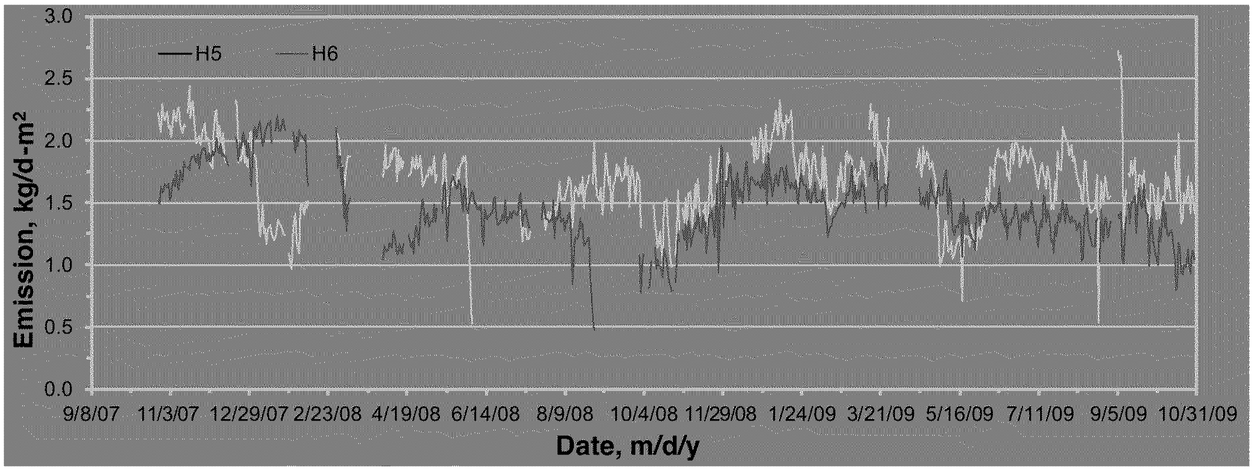


Figure 2.43. Daily mean area-specific CO_2 emission.

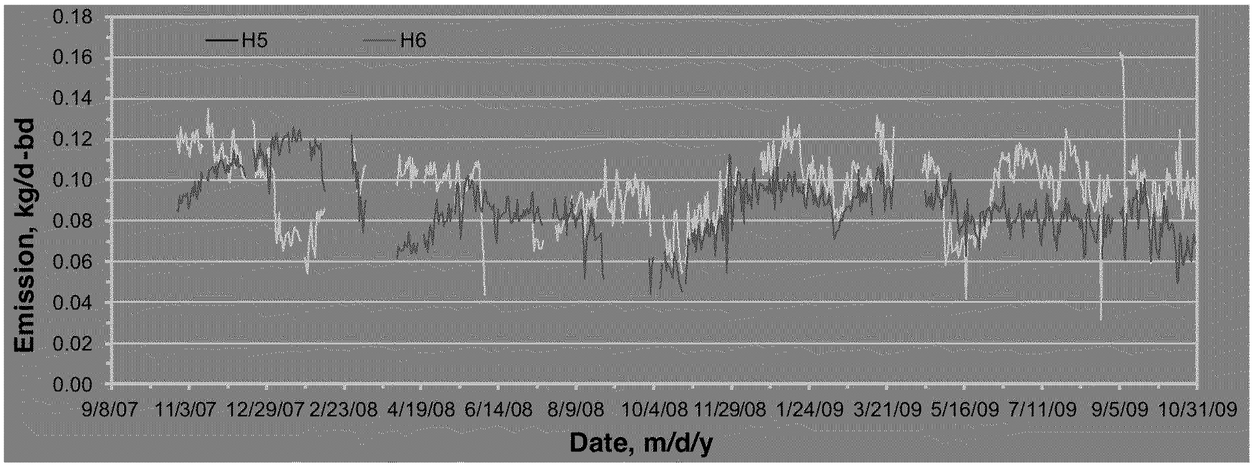


Figure 2.44. Daily mean hen-specific CO_2 emission.

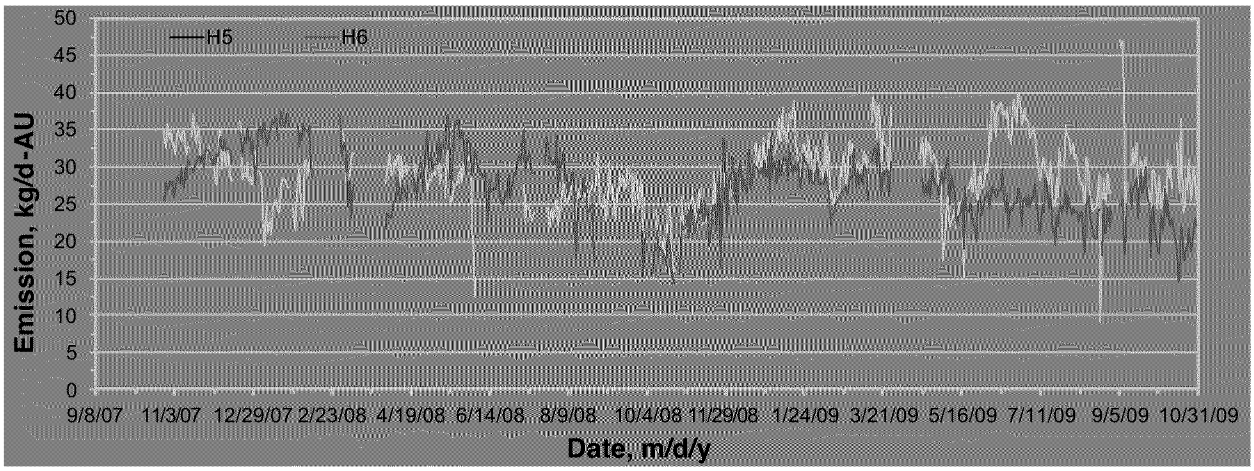


Figure 2.45. Daily mean LM-specific CO_2 emission.

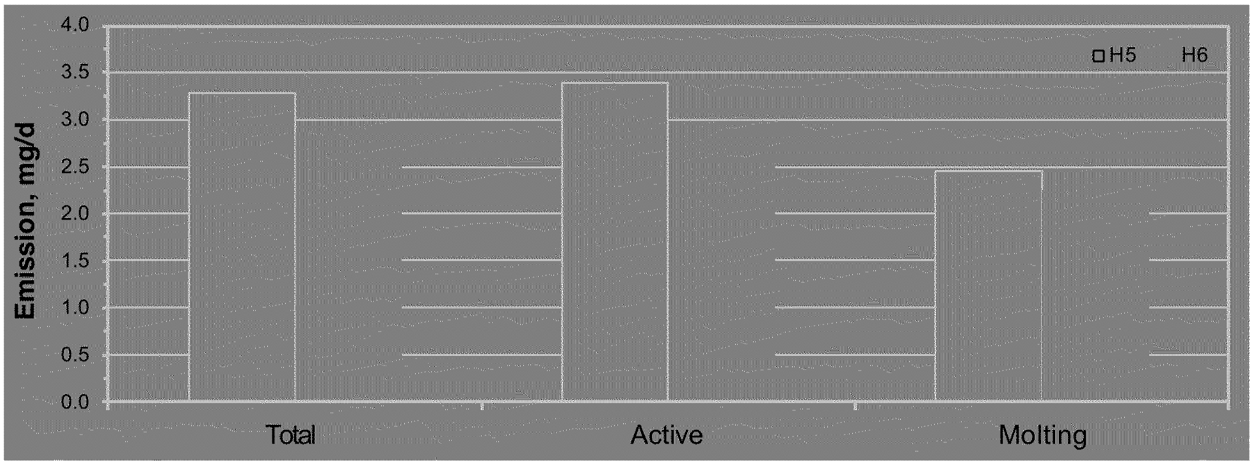


Figure 2.46. Comparison of house-specific CO_2 emission rates during the total period, active periods, and molting periods.

The main source of CO_2 production in a layer house is hen respiration, followed by manure. Emission prediction equations based on exhaust temperature and live mass density, for hourly, daily and weekly means were developed as shown in Equations 2.10 to 2.12:

Hourly:	$E = -220.9 + 70.57\ D - 8.69\ T$,	$R^2 = 0.143$	(2.10)
Daily:	$E = 505.6 + 56.33\ D - 22.47\ T$,	$R^2 = 0.295$	(2.11)
Weekly:	$E = 690.2 + 53.70\ D - 27.39\ T$,	$R^2 = 0.363$	(2.12)

Where E = CO_2 emission, kg d^{-1} m^{-2};
T = Exhaust temperature, °C; and
D = Live mass density, kg m^{-2}.

Table 2-26. Average means±SD (n) of CO_2 emission rates.

Variable	House 5	House 6
Daily mean emission rate		
House-specific, Mg d^{-1}	3.28±0.61 (585)	2.87±0.56 (606)
Area-specific, kg d^{-1} m^{-2}	1.68±0.31 (585)	1.47±0.29 (606)
Hen-specific, kg d^{-1} hd^{-1}	0.096±0.018 (585)	0.086±0.015 (605)
LM-specific, kg $d^{-1}AU^{-1}$	29±4.8 (585)	27.2±4.6 (605)
Egg-specific, kg d^{-1} doz^{-1}	39.0±182.9 (557)	22.0±100.4 (605)
Hourly mean emission rate		
House-specific, Mg d^{-1}	3.27±0.88 (14342)	2.86±0.78 (14780)
Area-specific, kg d^{-1} m^{-2}	1.68±0.45 (14342)	1.47±0.4 (14780)
Hen-specific, kg d^{-1} hd^{-1}	0.096±0.026 (14327)	0.086±0.022 (14745)
LM-specific, kg $d^{-1}AU^{-1}$	28.9±7.4 (14327)	27.2±6.9 (14745)

Live mass density, hen activity, hen age, feed and water intake, and exhaust temperature were significant influencing factors based on multivariate regressions of hourly, daily and weekly means (Table 2-27). The house effect was significant in all cases.

Table 2-27. Parameters influencing area-specific CO_2 emission, listed by significance.

Hourly Means		Daily and Weekly Means	
Parameter	**R^2**	**Parameter**	**R^2**
Atmospheric Pressure * LMD	0.158	**Daily Means**	
Hen Activity * Hen Age	0.303	LMD	0.246
House	0.361	LMD * Inlet Temp	0.326
LMD	0.426	House	0.471
Inlet Temp * Atmospheric Pressure	0.444	Exhaust Temp * Ventilation	0.497
Ventilation * LMD	0.459	LMD * Exhaust Temp	0.527
Time of Day * Solar	0.481	LMD * Ventilation	0.544
Ventilation * Solar	0.494	Hen Age	0.546
Solar * Hen Activity	0.503	Inlet Temp * Ventilation	0.551
Ventilation * Exhaust Temp	0.510	Manure Age	0.552
Inlet Temp * Inlet RH	0.516	LMD * Manure Age	0.560
Ventilation * Inlet Temp	0.532	LMD * Hen Age	0.570
Inlet Temp * LMD	0.544	Manure Age * Exhaust Temp	0.573
Atmospheric Pressure	0.548	Manure Age * Inlet Temp	0.581
Inlet RH * Hen Activity	0.551	Hen Age * Exhaust Temp	0.589
Ventilation * Static Pressure	0.557	Manure Age * Ventilation	0.589
Solar * Hen Age	0.559		
Static Pressure * Hen Age	0.562	**Weekly Means**	
LMD * Hen Age	0.567	Feed * Inlet Temp	0.470
Atmospheric Pressure * Hen Age	0.570	Water * Ventilation	0.602
Atmospheric Pressure * Hen Activity	0.575	Feed * Exhaust Temp	0.704
Inlet RH * Hen Age	0.577	House	0.714
Exhaust Temp * Hen Activity	0.580	Water	0.736
Hen Age	0.582	Eggs * Hen Age	0.743
Exhaust Temp * Inlet RH	0.585	Ventilation * Hen Age	0.752
Hen Activity	0.586	Ventilation * Manure Age	0.763
Time of Day * Ventilation	0.587	Hen Age * Manure Age	0.769
Time of Day * Hen Activity	0.589		
Time of Day * LMD	0.591		
Time of Day * Exhaust Temp	0.592		
Time of Day * Inlet RH	0.592		
Inlet RH	0.598		
Ventilation * Atmospheric Pressure	0.599		
Ventilation * Inlet RH	0.600		
Solar * Static Pressure	0.600		
Exhaust Temp * LMD	0.602		
Inlet Temp * Hen Age	0.602		
Time of Day	0.603		
Inlet Temp * Exhaust Temp	0.603		
Time of Day * Atmospheric Pressure	0.603		
Ventilation	0.604		
Inlet Temp	0.604		

Single variable regression was also performed between hourly CO_2 emission averages and key factors are shown in Table 2-282.28. The CO_2 emission was positively influenced by LMD, water consumption, feed intake, egg production, and hen activity (Figure 2.47). It was negatively influenced by temperature and hen activity.

Table 2-28. Correlations between area-specific CO_2 emission and other factors (* = p>0.05).

Parameter	Averaging interval	r
Live mass density	Daily	0.532
Live mass density	Weekly	0.530
Water consumption	Weekly	0.455
Feed intake	Weekly	0.427
Egg production	Weekly	0.382
Hen activity	Hourly	0.366
Atmosphere pressure	Hourly	0.276
Ambient RH	Hourly	0.149
Hen Age	Weekly	0.107*
Exhaust RH	Hourly	0.102
Solar radiation	Hourly	0.102
Hen age	Daily	0.030*
Manure age	Daily	-0.038*
Ventilation rate	Hourly	-0.074
Manure age	Weekly	-0.093*
Time of day	Hourly	-0.127
Average drop pressure	Hourly	-0.137
Ambient temperature	Hourly	-0.195
Exhaust temperature	Hourly	-0.212
Ventilation	Daily	-0.298
Ventilation	Weekly	-0.332
Exhaust temperature	Daily	-0.402
Inlet temperature	Daily	-0.438
Exhaust Temp	Weekly	-0.470
Inlet Temp	Weekly	-0.491
Wind speed	Hourly	-0.634

Note: n= 22160 to 24661, 1177-1188, and 143-173 for hourly, daily and weekly means.

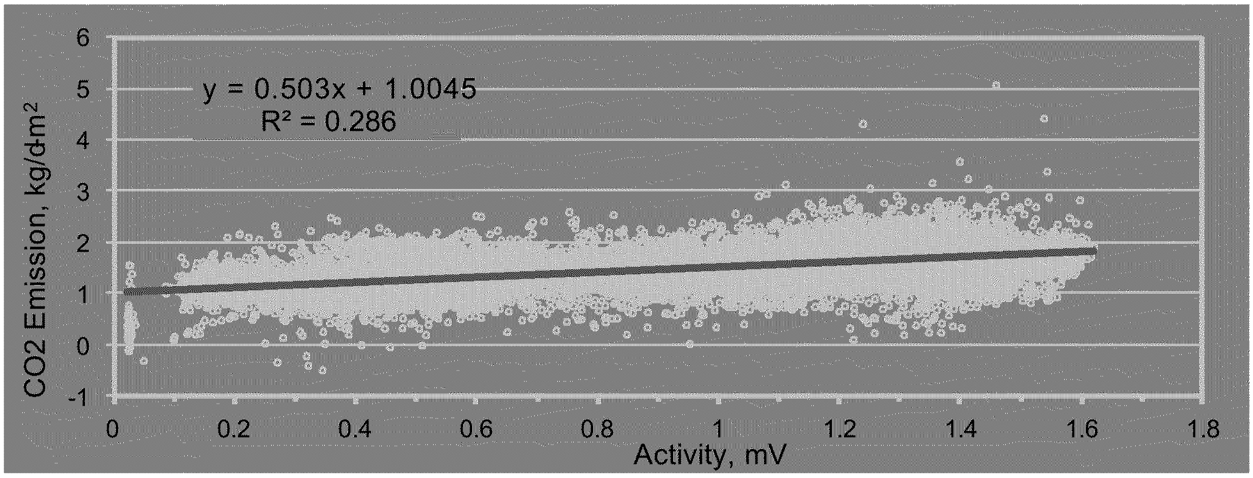


Figure 2.47. Correlations between area-specific H6 hourly CO_2 emission and hen activity.

2.4.9. Egg Specific Emission Rates

Emissions¬ on¬ dozen¬ "per eggs"¬ basis¬ were¬ calculated¬ by¬ dividing¬ the¬ ADM-house by the total number of eggs produced during the same period (Table 2-292.29).

Table 2-29. Mean emissions of air pollutants based on the eggs produced.

Pollutant Emission	H5	H6
PM_{10}, mg d^{-1} doz^{-1}	611	447
H_2S, mg d^{-1} doz^{-1}	21.8	18.6
NH_3, g d^{-1} doz^{-1}	15.7	14.8
CO2, kg d^{-1} doz^{-1}	1.58	1.33

2.4.10. Correlations between Pollutants

The correlations between pollutants are shown in Table 2-302.30. There were statistically significant correlations among all pollutants, with the exception of VOC where there was limited data to draw conclusions from, and CO_2 and PM_{10} emissions for house 6. There were both significant positive and inverse relationships between pollutants. This was expected based on the variation in NH_3 and H_2S, and the impact of molting periods on emission rates.

Table 2-30. Correlation between emission rates of different pollutants (* = p>0.05).

Parameter	Pearson correlation coefficient Number of observations			
	NH_3	H_2S	PM_{10}	CO_2
House 5				
NH_3[a]	-			
H_2S[a]	0.388* 13641	-		
PM_{10}[a]	0.098* 10377	0.341* 10337	-	
CO_2[a]	0.489* 14316	0.463* 13666	0.165* 10396	-
VOC[b]	-0.467 6	-0.431 6	-0.190 5	0.178 6
VOC[b] (10/2/09 sample excl.)	0.729 5	0.500 5	0.971 5	0.223 4
House 6				
NH_3[a]	-			
H_2S[a]	0.711* 14072	-		
PM_{10}[a]	-0.144* 11764	0.061* 12245	-	
CO_2[a]	0.576* 14750	0.593* 14097	-0.002 11791	-
VOC[b]	-0.512 5	-0.408 5	-0.192 5	-0.360 5
VOC[b] (10/2/09 sample excl.)	-0.886 4	-0.772 4	0.623 4	0.588 4

[a]Hourly area-specific emission rates
[b]Daily house-specific emission rates

2.5. Uncertainties in Airflow and Emission Rate

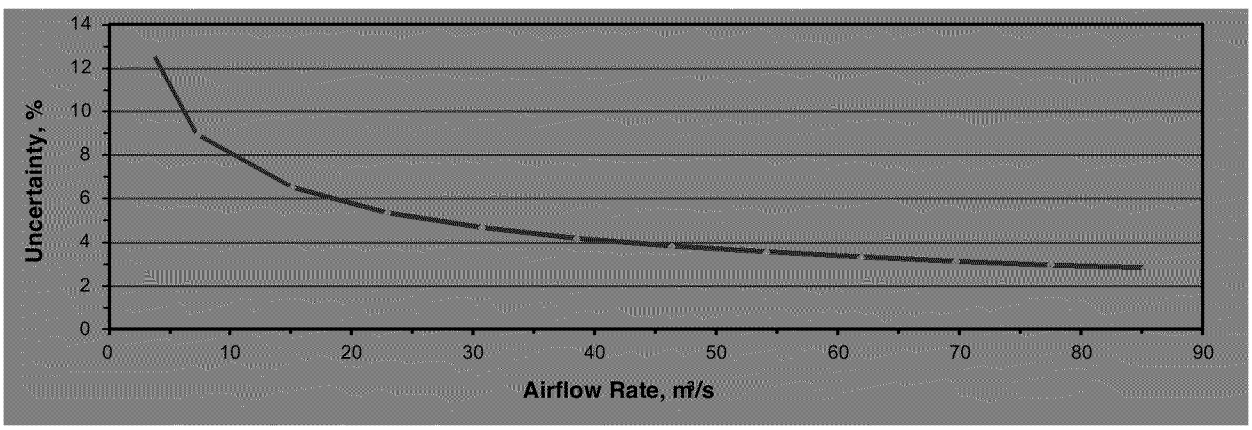


Figure 2.48. Dependence of airflow uncertainty on total airflow rate.

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2.6. Changes to the CA2B EPA Report

The following changes to the CA2B final report were submitted to the EPA.

- In Section 4.7, the table number for daily mean NH_3 concentrations was missing.
- ,Q 6HFWLRQ ┤◀→☼ WKH VHQWHQFH ... NH_3 emissions from H5 and H6 are tabulated in ... +
  7DEOH ([DQG SORWWHG LQ)LJXUH [IRU WKH HQWLUH ...
  table and figure values. 7KH FRUUHFWHG VHQWHQFH ... NH_3 emissions from H5 ... GDLO\ PHDQ ...
  and H6 are tabulated in Table E10 and plotted in)LJXUH ← IRU WKH HQWLUH W...
- ,Q 6HFWLRQ ┤◀→☼ WKH VHQWHQFH ... hen-specific NH_3 emission rates from H5 and H6
  were 950±487 (n=583) and 944±859 (n=602) mg d^{-1} hen^{-1}☼ UHVSHFWLYHO\. The ☼ LV FR...
  units of hen-specific NH_3 emission in Table E10 should be g d^{-1} hen^{-1} for both houses.
- ,Q 6HFWLRQ ┤◀┴☼ WKH VHQWHQFH ³7KH ... in H5 and ... GHQVLW\ RI WKH ...
  between 0.37 and 0.46 kg·m^{-3} LQ +├ ♂ PHDVXUHPHQWV WDNHQ RQ WZR ...
  shows incorrect units for manure density. The sentHQFH VKRXOG EH ³7KH GHQVLW...
  manure was 0.44 kg L^{-1} in H5, and between 0.37 and 0.46 kg L^{-1} in H6 (measurements
  taken on two consecutive days).

3. DISCUSSION OF THE IN2B DATA

3.1. Introduction

3.1.1. Facilities

The egg production facility was located in Wabash County, 143 km (89 mi) NE of Purdue University (West Lafayette, IN) with a total driving time of 2 hrs one way. The facility consisted of an egg-processing plant, three high-rise caged-hen houses, seven manure-belt caged-hen layer houses, two cage-free laying houses, and one free-standing manure shed. All of the houses were oriented E-W and were spaced 17-18 m (56-60 ft) apart (Figure 3.1). The capacity of the complex was 2.9 million hens. Hens were raised in low-density conditions according to industry standards. A corn soy based diet was delivered to the hens in a trough feeder at the front of the cages.

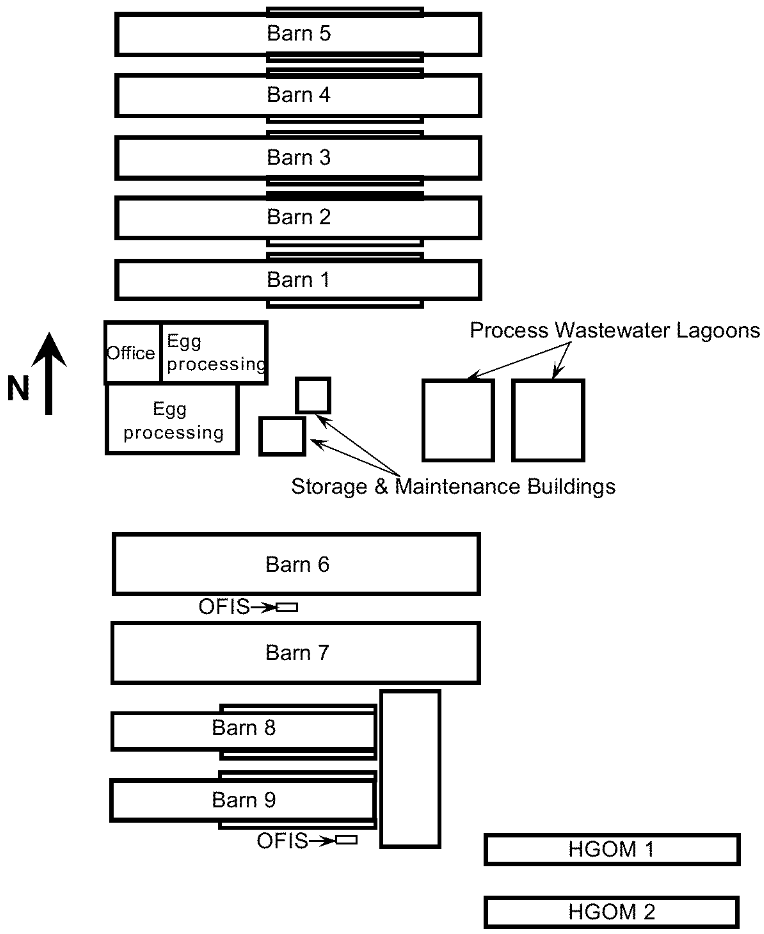

Figure 3.1. Layout of facility including monitored houses 8 and 9 and the manure shed.

Houses 1-5 were built in 1980 and remodeled in 2005. House 1 was converted to manure-belt in 2007. Houses 2 and 3 had manure drying tunnels that were fully enclosed. Houses 2 through 5 used manure belt and were attached to the manure shed at the east end of each house. Houses 6 and 7 were built in 1997 and were houses NAEMS' IN2H monitoring

Houses 8 and 9 were built in 2004 and were used as IN2B monitoring site. Both houses were oriented E-W and were spaced 18 m apart. The manure shed for houses 8 and 9 was oriented N-S and was located 3 m from the E end of those two houses and was also constructed in 2004. Both houses were mechanically ventilated and oriented east-west. Further descriptive parameters of the houses are given in Table 3-13.1.

Table 3-1. Characteristics of houses at the IN2B site.

Descriptive Parameters	Houses 8-9	Shed
House number and type	2 manure belt	1 naturally ventilated
Year(s) of construction	2004	2004
House orientation	E-W	N-S
House dimension (LxW)	140 m x 19.5 m	61 m x 30.5 m
Ridge height	11.5 m	11.5 m
Sidewall height	7 m	7 m
House spacing	18 m	3 m
House capacity and genetics of hens	280,000 hens, W36	-
Average weight	1.5 kg	-
Hen occupation	700 d	-
Molting	Yes	-
Number of tiers of /rows of cages	10 / 7	-
Type of cages and hen space	Facco, 1.5 m^2/hen	-
Manure collection method	belts	belts
Manure accumulation capacity	3 d	1-180 d
Ventilation type	Mechanical	Natural
Number and type of air inlets	7 flat baffle over row	3 Openings
Inlet control basis/adjustment method	Temperature/Cable	-
Controls vendor/manufacturer	Fancom	-
Walls with fans	N, S, E	-
Ventilation fans and fan spacing	88 fans with varies spacing	-
Number of variable speed fans	14 each house	-
Fan manufacturer and diameter	Aerotech, 1.3 m	-
Number of ventilation stages	14	-
Number of temperature sensors	12	-
Emergency ventilation	Gen Set	-

Besides the other buildings, the only possible on-farm source of contaminants is the anaerobic lagoon that receives wastewater from the egg-washing process. The farm is in an agricultural area with small pockets of trees. There are no identifiable off-farm sources of contaminants, other than fields that periodically receive manure, within one mile of the farm site.

3.1.2. Weather Conditions

The weather conditions at the site are shown in Table 3-23.2. According to historical climate, daytime average high temperatures range from -1°C in the winter to 29°C in the summer. Average overnight lows range from -9°C in winter to 17°C in summer. Typical prevailing winds for the region are from the west in the winter and southwest during the rest of the year.

Table 3-2. Monthly averages for weather conditions at the IN2B site.

Month	**Temperature, °C**			**Wind speed, km h^{-1}**	**Wind direction**
	High	**Low**	**Mean**		
January	-1	-9	-5	21	W
February	1	-8	-3	19	W
March	8	-2	3	21	W
April	15	4	9	20	W
May	22	10	15	17	SW
June	27	15	21	16	SW
July	29	17	22	14	SW
August	28	16	21	13	SW
September	24	12	17	14	SW
October	17	6	11	16	SW
November	10	1	4	18	SW
December	2	6	-2	19	W
Annual average	15	6	9		

Source: http://www.weather.com/weather/wxclimatology/monthly/46992

3.2. Quality Control and Quality Assurance of Carbon Dioxide Measurement

The NAEMS EPA report has included gas analyzers for NH_3 and H_2S, but not the carbon dioxide (CO_2). Quality control and quality assurance for carbon dioxide measurement is presented below.

While carbon dioxide was not one of the regulated pollutants studied by the NAEMS, this measurement provided valuable information on ventilation performance (Heber et al., 2001; Blanes and Pedersen, 2005; Liang et al., 2005; Heber et al., 2006). It also provided a useful check on the integrity of the gas sampling system; readings of 100 ppm or higher in zero air during z/s checks were considered indicative of a leak in the sampling system.

Carbon dioxide concentration was measured using a photoacoustic infrared INNOVA 1412 (LumaSense Technologies A/S, Ballerup, Denmark). Multipoint calibrations (MPCs) using zero air and CO_2 in span nitrogen (Praxair, Indianapolis, IN) were conducted six times to assess linearity. Both zero air and calibration gases were delivered via a challenge line to the sampling point at the south side manure drying tunnel of H9 using a 7-port gas dilutor (Model 4040, Environics, Tolland, CT). The R^2 values of all MPC reached 0.99 (Table 3-33.3), indicating linearity of instrument response to standard CO_2 between 0 and 9000 ppm. Figure 3.2 plots the responses of the sampling and measurement system to an example MPC.

Table 3-3. Multipoint CO_2 measurement calibration and results at IN2B.

Date	# of points	Span concentration, ppm		R^2
		Minimum	Maximum	
01/31/08	4	1450	4500	0.99
11/05/08	12	100	9000	0.99
01/05/09	6	100	4000	0.99
04/09/09	6	500	8000	0.99
06/11/09	4	1500	4500	0.99
01/14/10	7	500	5000	0.99

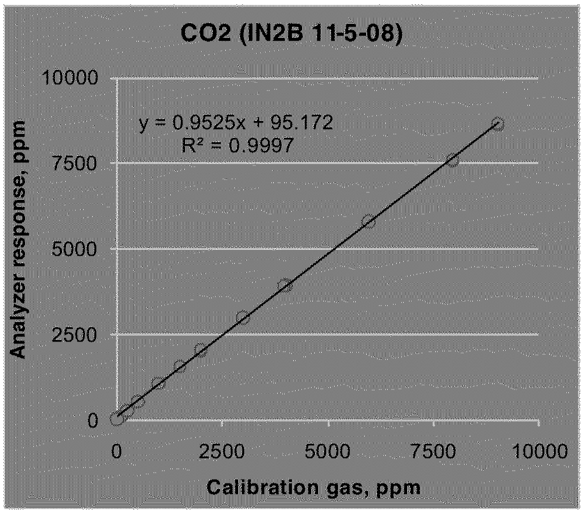

Figure 3.2. An example MPC of CO_2 measurements at IN2B.

Precision checks were conducted periodically using zero and span gases (Z/S checks), also delivered via the dilutor through the challenge line, and responses were recorded to monitor changes in system performance over time. Span checks were conducted with 4000 and 4500 ppm CO_2 (Figure 3.3 and Figure 3.4).

In five of the weekly Z/S checks (on 3/13, 3/16, 3/26, 6/11, and 6/19/08), the responses of the system to zero air exceeded 60 ppm CO_2, indicating leakage of the sampling system. The gas measurement data during these periods were therefore invalidated.

The average responses of the analyzer to zero and span gas applications were assessed, and the results were combined based on changes to the instrument or gas sampling system to create linear correction models (Table 3-43.4). The models were used to correct instrument readouts.

Table 3-4. Correction equations for CO_2 concentrations at different monitoring periods.

Start date and time	End date and time	Correction linear model
11/1/07 0:00	1/24/08 1:56	Y=0.9809x-32.1
1/24/08 1:56	5/18/08 18:40	Y=0.8977x-24.6
5/18/08 18:40	7/9/08 15:04	Y=1.0340x-48.8
7/9/08 15:04	3/10/09 19:48	Y=1.0146x-37.6
3/10/09 19:48	1/15/10 0:00	Y=1.0715x-44.2

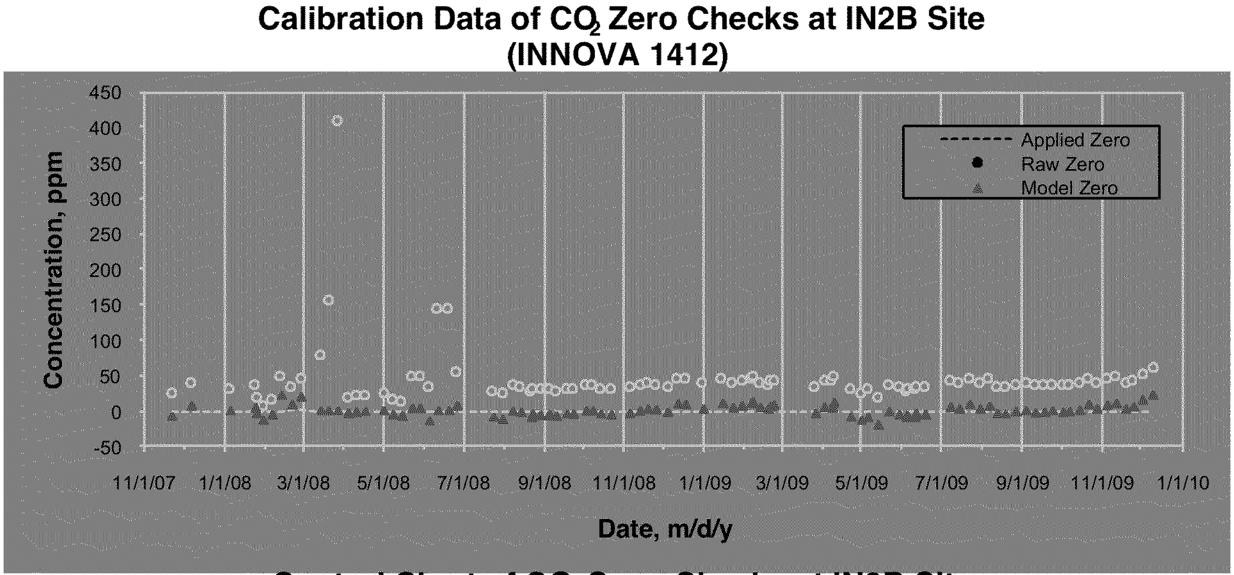

Figure 3.3. Results of weekly zero checks of CO_2 measurement with Innova 1412 at IN2B.

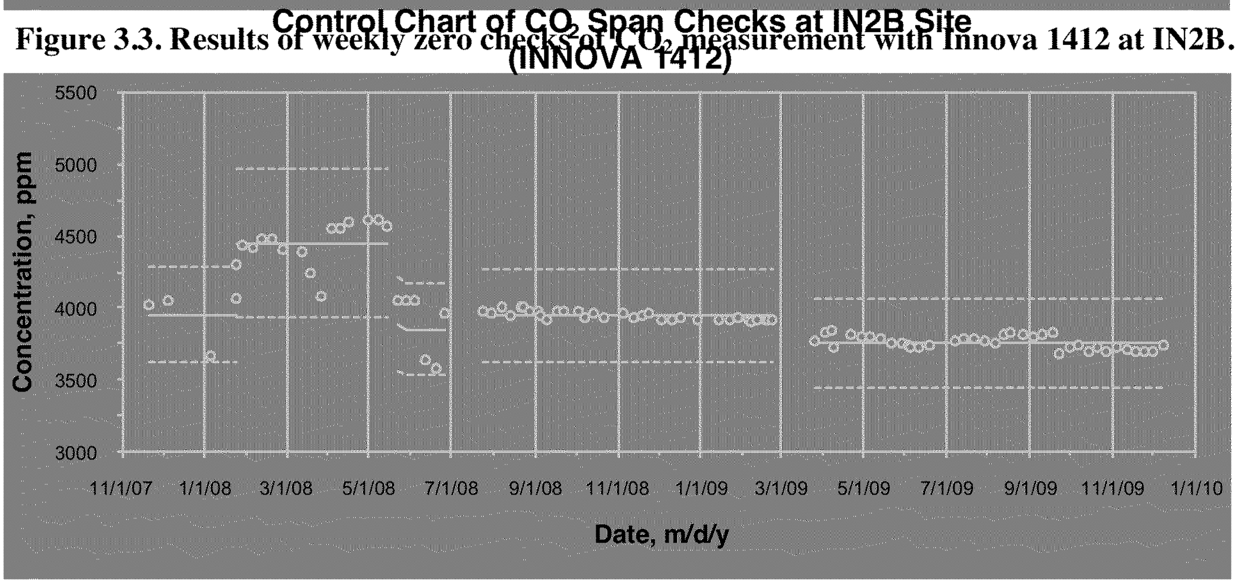

Figure 3.4. Results of weekly span checks of CO_2 measurement with Innova 1412 at IN2B.

3.3. Results

3.3.1. Animal Characteristics

3.3.1.1. Animal Inventory

The hen inventories of both houses during the study are presented in Figure 3.5. A new flock of hens was placed in house 8 at the end of 2007 and remained there until the end of 2009. The existing flock in H9 was removed in October 2008 and a new flock was placed at the beginning of November 2008. Flock sizes decreased steadily after initial placements because of mortality. The initial and final inventories of H8 were 262,600 on 1/1/08 and 228,600 on 12/31/09. The average inventory reduction was 46 hens/d. The initial inventory of the first flock in H9 were 257,970 on 1/1/08 and decreased by 63 hens/d until the flock was removed.

The initial and final inventories of H9 were 250,800 on 11/8/08 and 238,000 on 12/31/09 for an average reduction of 31 hens/d. Table 3-53.5 lists the number of days of valid data, minimum and maximum daily means (DM), and average daily mean (ADM±SD) house inventories for the first and second years, and for both years.

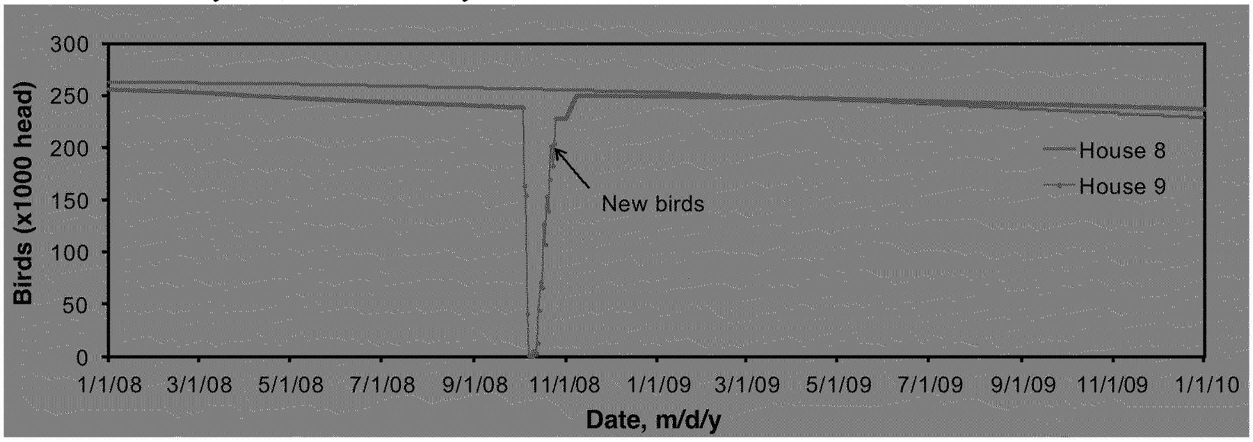

Figure 3.5. Hen inventories during the two-year monitoring at IN2B.

Table 3-5. Annual and 2-yr statistics of flock at site IN2B.

Variable	House 8			House 9		
	Hens,┐ 100	Wt, kg	Eggs, k	Hens,┐ 100	Wt, kg	Eggs, k
2-yr valid days, d	731	731	731	711	704	731
Minimum DM	229	1.20	0	0	1.15	0
Maximum DM	263	1.52	245	257	1.53	237
1st yr ADM±SD	259±2.8	1.42±0.03	211.4±39.6	248±5.8	1.44±0.09	151.3±74.6
2nd yr ADM±SD	241±7.1	1.42±0.07	154.0±61.1	245±3.7	1.39±0.05	187.1±63.7
2-yr ADM±SD	250±10.2	1.42±0.05	182.7±58.9	246±10.5	1.41±0.08	169.2±71.7

3.3.1.2. Animal weight

The average hen weight was 1.42±0.07 and 1.39±0.05 kg for houses 8 and 9, respectively. The average weights in both houses were relatively stable except when new flocks were placed in houses and when the flocks underwent molting (Figure 3.6). Molting occurred at the beginning of 2009 in house 8 and at the beginning of 2008 and end of 2009 in H9. The average hen weights with different integration times are given in Table 3-53.5.

3.3.1.3. Egg Production

Clear patterns of decreasing egg production after a new flock was placed in H9 and after molting in both houses were exhibited (Figure 3.7). The highest egg production occurred between February and March 2008 in H8 and between January and February 2009 in H9 after new flocks were placed. The combined 2-yr average egg production during empty houses and molting were 182,710 and 169,150 eggs/d for houses 8 and 9, respectively (Table 3-53.5).

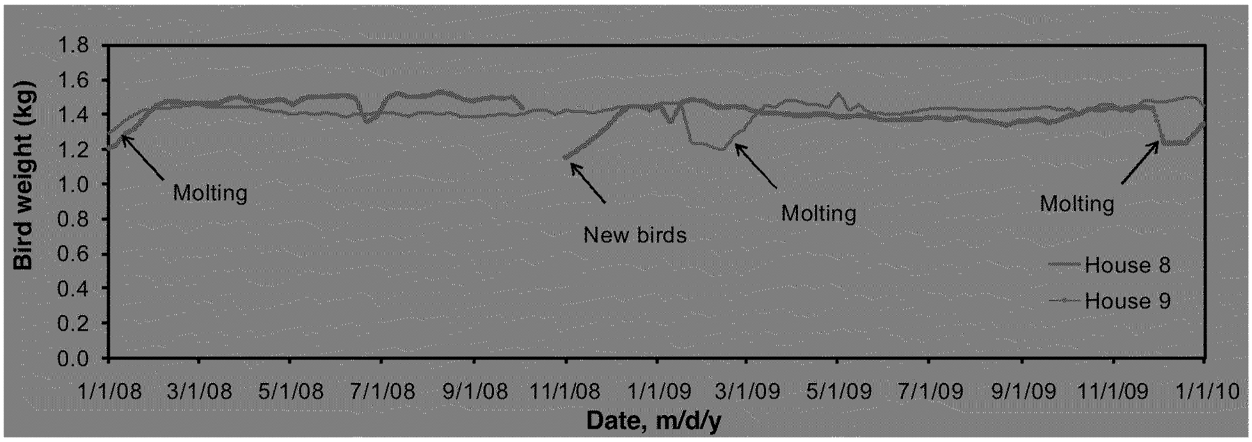

Figure 3.6. Average hen weights at IN2B.4

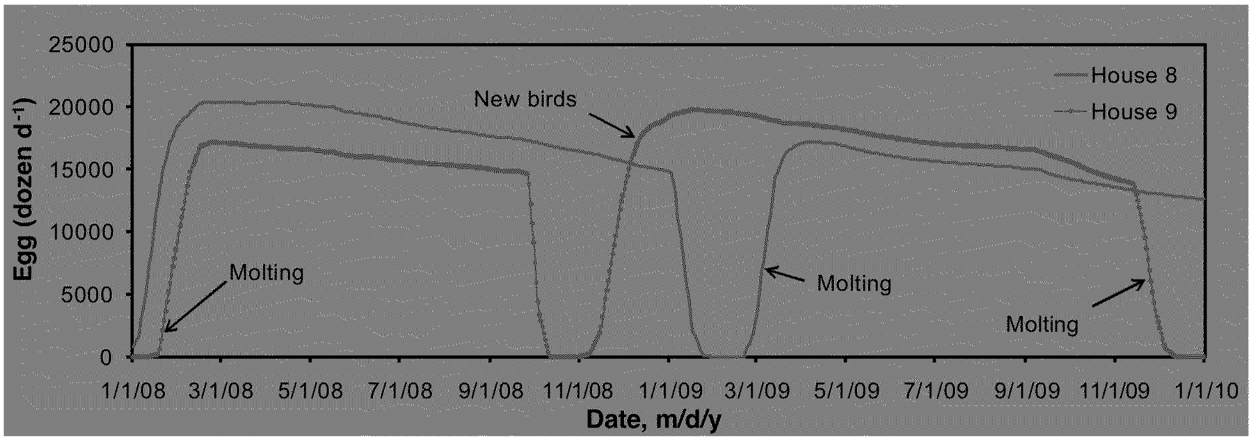

Figure 3.7. Daily egg production at IN2B.

3.3.1.4. Comparison between Houses

Although differences were observed in animal characteristics due to management practices between the houses, the 2-yr ADM hen inventory and average weight of the two houses were comparable (Table 3-63.6). House 8 had 1.7% greater flock size and 0.7% greater hen weight than those of H9. However, due to differences in starting dates of new hen flocks and molting, the egg production of H8 was 8% higher than H9 during the 2-yr study. The differences in these characteristics were more visible when the data were separated into two annual means. This indicated that the multi-year study generated better data that revealed annual variations.

Table 3-6. Comparison of hens between the two houses at IN2B.

Parameter	H8/H9 hen, %	H8/H9 weight, %	H8/H9 egg, %
2-yr valid days	102.8	103.8	100.0
Minimum DM	n.a	104	n.a
Maximum DM	102.2	99.3	103.2
1st yr ADM±SD	104.4	98.6	139.7
2nd yr ADM±SD	98.5	102.2	82.3
2-yr ADM±SD	101.7	100.7	108.0

3.3.2. Environmental Conditions and Airflow

3.3.2.1. Temperatures

The 2-yr ADM exhaust air temperatures in houses 8 and 9 were 26.8±2.0 and 26.5±2.5°C Mean±SD), respectively, while the 2-yr ADM ambient temperature was 12.0±10.9°C (Table 3-73.7). The daily mean indoor air temperatures ranged from 20.0 to 31.0 ºC in H8 and 14.9 to 31.2 ºC in H9. The lowest value in H9 occurred in October, 2008 when the house was emptied. The daily mean exhaust temperatures showed seasonal variations corresponding to seasonal variations of ambient temperatures (Figure 3.8). The exhaust temperatures were also affected by flock size and controlled by the house ventilation system.

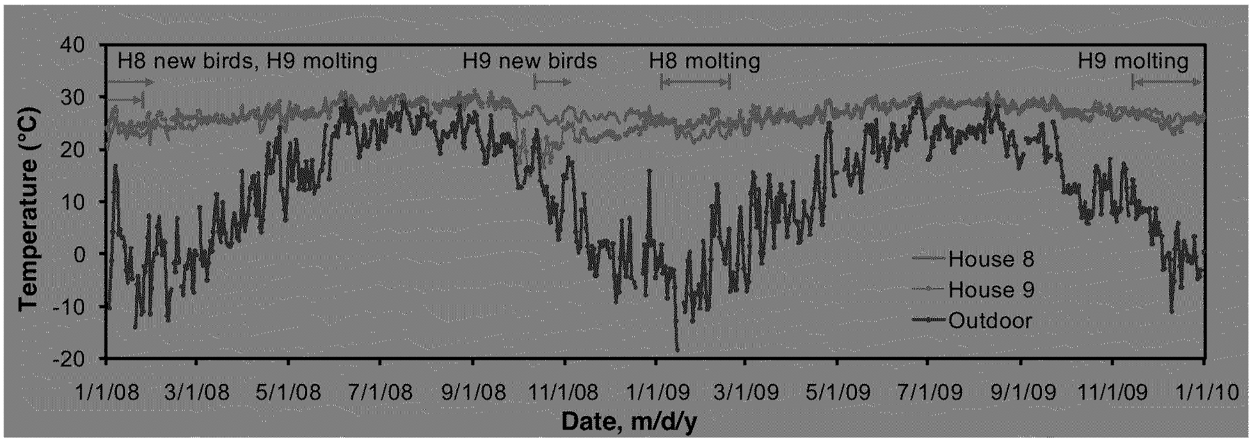

Figure 3.8. Daily mean indoor and ambient temperatures at IN2B.

The lowest daily mean exhaust temperatures close to 15 ºC occurred in October, 2008 in H9 when it was being emptied. The highest daily mean indoor temperatures of about 31 ºC were observed in July and August in both 2008 and 2009 during full-house days. The temperature differences between the houses were the largest from October, 2008 to March, 2009 when old flock of hens were removed and new hens were filled in H9. The indoor temperature was primarily affected by the flock size and controlled by the house ventilation.

3.3.2.2. Static Pressure

The house pressure, which was the mean of three static pressures across the east, north, and south walls, in H8 was -36.5 Pa, compared with that of -48.9 Pa in H9, during the two-year monitoring (Table 3-73.7.). The daily mean data in Figure 3.9 also clearly indicate that the absolute pressure in H9 were about twice as high as in H8 for most of the days. The absolute pressure in H9 was similar or smaller than H8 only in a limited number of days, including the days when H9 was empty in October, 2008 between two flocks of hens. Field inspection confirmed that the conditions of high absolute pressure in H9 was related to the insufficient opening of the ceiling air inlets.

Table 3-7. Annual and 2-yr statistics of temperature, pressure, and airflow at IN2B.

Parameter	Temperature, °C			Pressure, Pa		Airflow, m^3/h-hen	
	H8	H9	Ambient	H8	H9	H8	H9
2-yr valid days	712	712	701	712	712	693	678
Minimum DM	20.0	14.9	-18.4	-66.6	-66.6	0.26	0.29
Maximum DM	31.0	31.2	29.6	-11.5	-0.1	9.16	9.22
1st yr*	26.6±2.0	26.0±3.0	12.2±11.1	-37.7±8.8	-48.9±10.9	2.16±1.63	2.31±1.66
2nd yr*	27.0±2.0	26.9±1.6	11.7±10.7	-35.4±10.5	-48.8±9.0	2.00±1.41	1.90±1.41
2-yr *	26.8±2.0	26.5±2.5	12±10.9	-36.5±9.7	-48.9±10.0	2.08±1.53	2.10±1.55

*ADM±SD

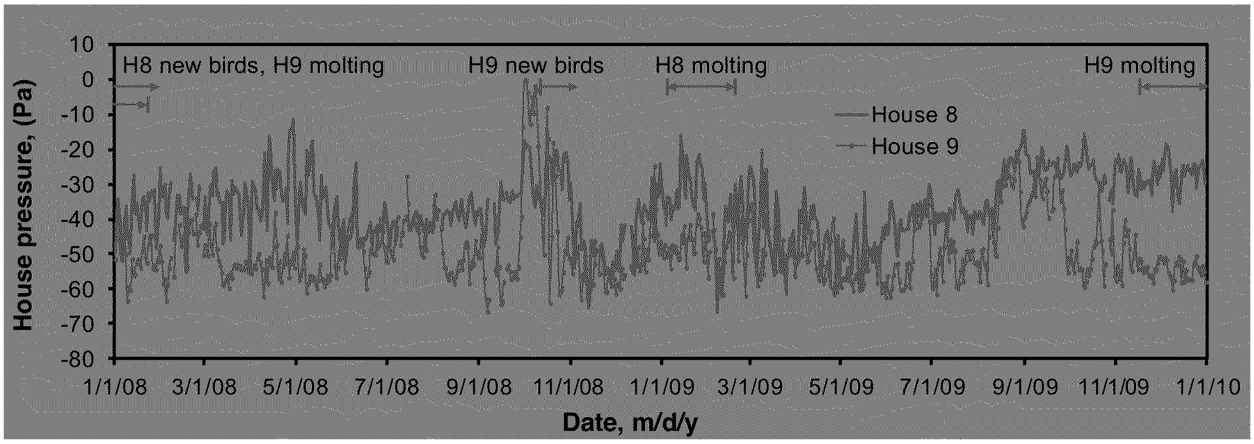

Figure 3.9. Daily mean house static pressure at IN2B.

3.3.2.3. *Ventilation*

A total of 693 and 678 complete data days of hen-specific ventilation rates were obtained in houses 8 and 9, respectively. The two-year mean hen-specific ventilation rates in houses 8 and 9 were 2.08±1.53 and 2.10±1.55 m^3 h^{-1} hen^{-1}, respectively (Table 3-73.7). The two-year mean ventilation rates in houses 8 and 9 were 145and 142 m^3 s^{-1}, respectively.

The monthly mean house ventilation rates were higher from June to August than in other months of the year due to higher ambient temperatures. The two-year continuous monitoring provided unique data that indicated annual ventilation variations. Significant differences in monthly ventilation rates in July between 2008 and 2009 compared with June and August were related to the difference in monthly mean ambient temperatures. In 2008, the monthly ambient temperature of 25.4ºC was higher in July compared with 23.8ºC in June and 23.8ºC in August. However, the monthly mean ambient temperatures in 2009 were 23.7, 22.8, and 23.3ºC for June, July, and Aug., respectively. July had lower temperatures than the two adjacent months. The minimum monthly mean ventilation rates were 0.59 and 0.81 m^3 h^{-1} hen^{-1} in Feb. 2008 for houses 8 and 9, respectively. The maximum monthly means were 4.87 and 5.01 m^3 h^{-1} hen^{-1} in July 2008, respectively.

The daily mean hen-specific ventilation rates (Figure 3.10) generally followed the seasonal ambient temperature variations. However, the minimum and maximum daily mean ventilation rates did not occur on the coldest and hottest days, respectively. The minimum daily means occurred on 2/10/08 when the daily mean ambient temperature was -11.8 ºC and were 0.26 and

0.29 $m^3 h^{-1} hen^{-1}$ for houses 8 and 9, respectively. The coldest day had a daily mean temperature of -18.4 ºC. The maximum daily mean ventilation rates were 9.16 and 9.22 $m^3 h^{-1} hen^{-1}$ for houses 8 and 9, respectively, on 6/28/09 when the daily mean ambient temperature was 26.0 ºC, which was not the maximum (29.6ºC).

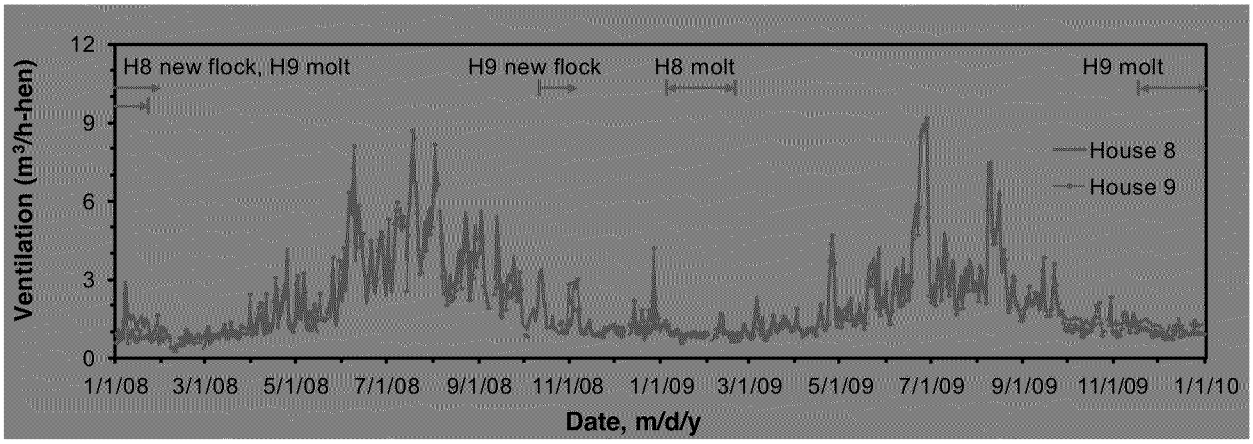

Figure 3.10. Daily mean hen-specific ventilation rate at IN2B.

3.3.2.4. Comparison between Houses

The 2-yr ADM indoor temperature and hen-specific house airflow in H8 were 101.1% and 99.0% of those of H9, respectively (Table 3-83.8). The differences between the two houses were about 1% for both variables. However, the 2-yr ADM static pressure in H8 was only 74.8% of H9. The exceptional large difference of 78-fold daily maximum static pressure between the two houses occurred because H9 had measurements while it was empty.

Table 3-8. Comparison of airflow, temperature, and pressure between houses at IN2B.

Parameters	H8/H9 Indoor T	H8/H9 dP	H8/H9 Airflow
Valid day	100.0%	100.0%	102.2%
Minimum DM	134.2%	100.1%	89.2%
Maximum DM	99.3%	7865.0%	99.4%
1st yr ADM±SD	102.3%	77.0%	93.5%
2nd yr ADM±SD	100.5%	72.6%	105.3%
2-yr ADM±SD	101.1%	74.8%	99.0%

3.3.3. Ammonia Concentration and Emission

The 2-yr ADM inlet NH_3 concentrations averaged 0.7±1.0 and 0.8±1.4 ppm in houses 8 and 9, respectively (Figure 3.11). The house inlet concentrations were high in cold weather and relatively low in warm and hot weather. The maximum daily mean inlet concentrations were 7.5 and 9.1 ppm for H8 and H9, respectively, and occurred in winter when the house exhaust NH_3 concentrations were also high (Table 3-93.9).

The two-year mean NH_3 concentrations at fan exhausts averaged 13.3±9.1 and 12.9±10.5 ppm at H8 and H9, respectively. It was 8.1±6.0 ppm at the manure shed's air outlet. Seasonal variations of the exhaust NH_3 concentrations (Figure 3.12) were closely related to variations of ambient temperatures and house ventilation rate. Low concentrations were observed between the beginning of May and the end of October. The exceptionally low NH_3 concentrations during molt occurred because the hens were provided with limited feed, resulting in greatly reduced manure production and hence NH_3 production. The concentrations of NH_3 were also lower during the first month of a new flock. The two-year mean maximum daily NH_3 concentrations at the exhausts were 13.3±9.1, 12.9±10.5, and 8.1±6.0 ppm for H8 and H9, and the shed, respectively.

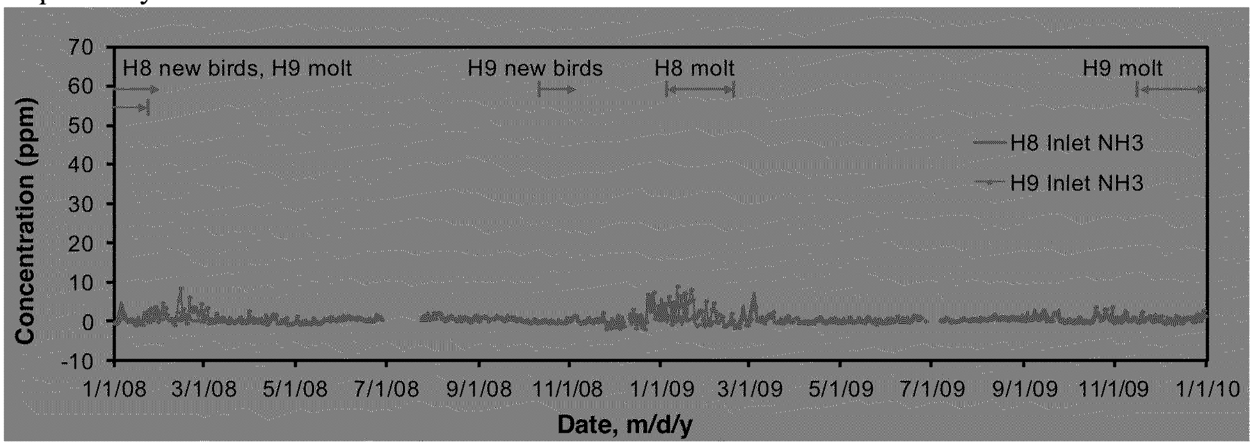

Figure 3.11. Daily means of house inlet ammonia concentrations.

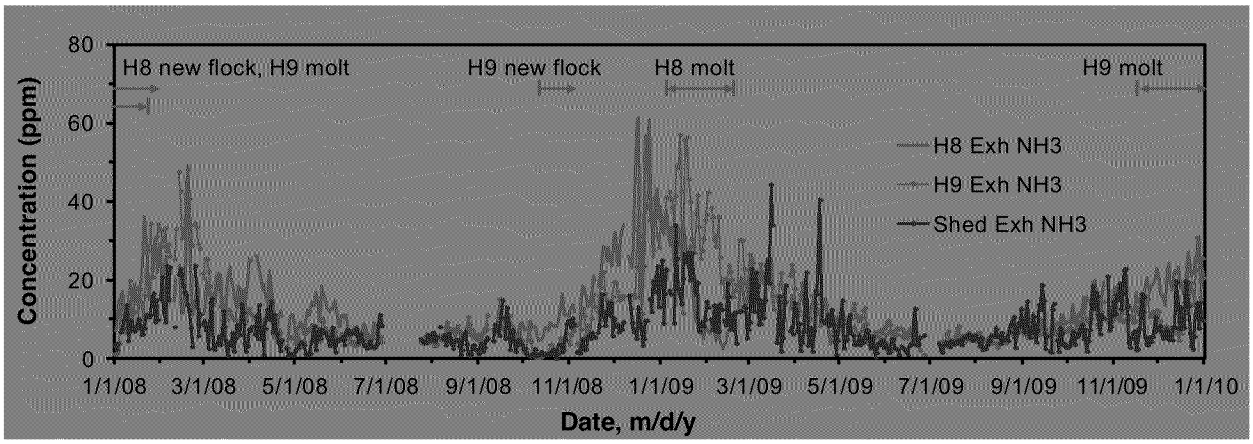

Figure 3.12. Daily means of house and manure shed exhaust ammonia concentrations.

Table 3-9. Annual and 2-yr statistics of house inlet and exhaust ammonia concentrations at IN2B.

Parameter	H8 Inlet	H9 Inlet	H8 Exhaust	H9 Exhaust	Shed
2-yr valid days, d	691	689	668	667	656
Minimum DM, ppm	-1.5	-1.7	1.1	0.2	0.1
Maximum DM, ppm	7.5	9.1	61.3	57.2	44.5
1st yr ADM±SD, ppm	0.6±0.9	0.8±1.4	14.6±10.2	12±10.2	6.7±4.8
2nd yr ADM±SD, ppm	0.7±1.0	0.9±1.4	12.0±7.8	13.8±10.6	9.3±6.7
2-yr ADM±SD, ppm	0.7±1.0	0.8±1.4	13.3±9.1	12.9±10.5	8.1±6.0

The 2-yr ADM house inlet and exhaust NH_3 concentrations in H8 were 87.5% and 103.1% of those of H9, respectively (Table 3-93.9). Annual variations were shown for exhaust concentrations. The first year annual mean concentration in H8 was 21.7% higher than H9. However, it was 13% less in the second year.

The 2-yr ADM concentrations at the exhaust were comparable with reports from other countries, e.g., 8.3 ppm in England, 29.6 ppm in the Netherlands, 25.2 ppm in Denmark, and 36.7 ppm in Slovenia (Koerkamp et al., 1998; Dobeic and Pintaric, 2011). A recent study in Taiwan showed NH_3 concentrations in hen cages ranged from 0.5 to 12.5 ppm, which was also comparable to the manure-belt houses. However, concentrations from manure disposal sites were detected as high as 500 ppm at 10 cm above the manure surface (Cheng et al., 2011).

Figure 3.13 shows the variations of daily mean NH_3 emissions from both houses and the manure shed. Seasonal variations of NH_3 emissions exhibited a similar pattern as the concentrations. The higher house emission rates corresponded to the higher concentrations from the beginning of November to the end of April and were believed to be related to low ventilation rates and higher manure moisture content. Because of the relatively constant inventories except for the short empty house period between flocks, the daily LM- and hen-specific NH_3 emission rates (Figure 3.14 and Figure 3.15) exhibited seasonal patterns similar to house emissions.

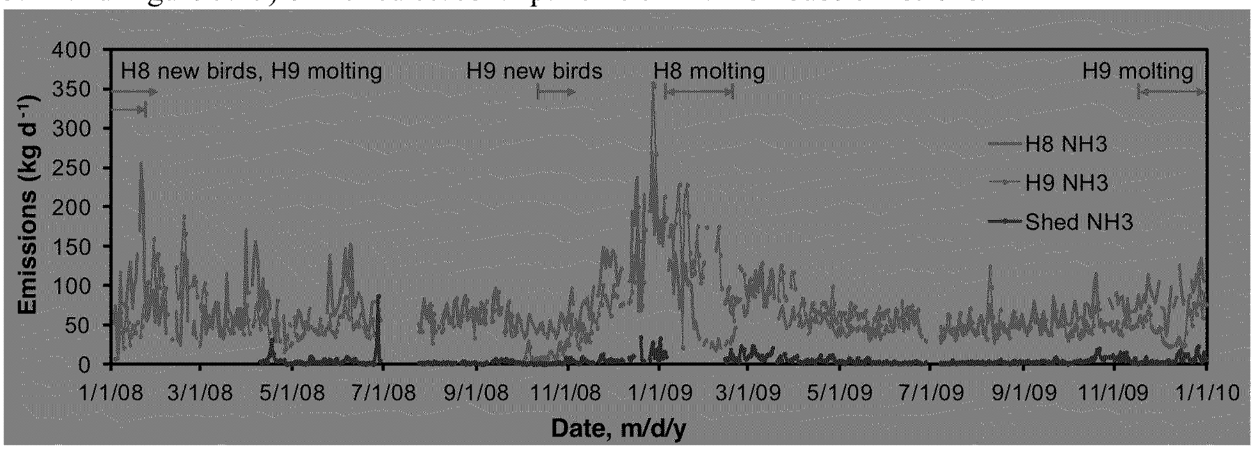

Figure 3.13. Daily means of ammonia emissions from the houses and the manure shed.

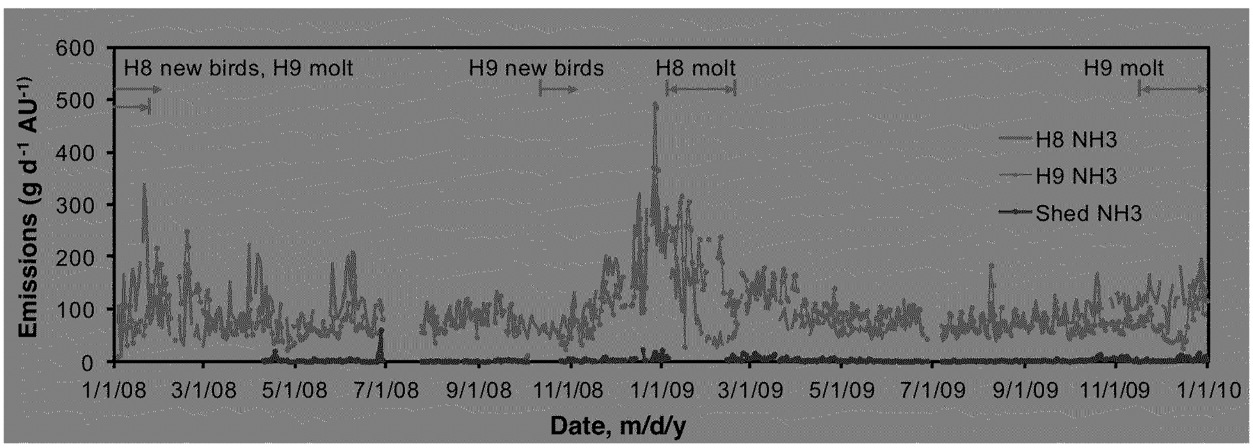

Figure 3.14. Daily LM-specific means of ammonia emissions from houses and manure shed.

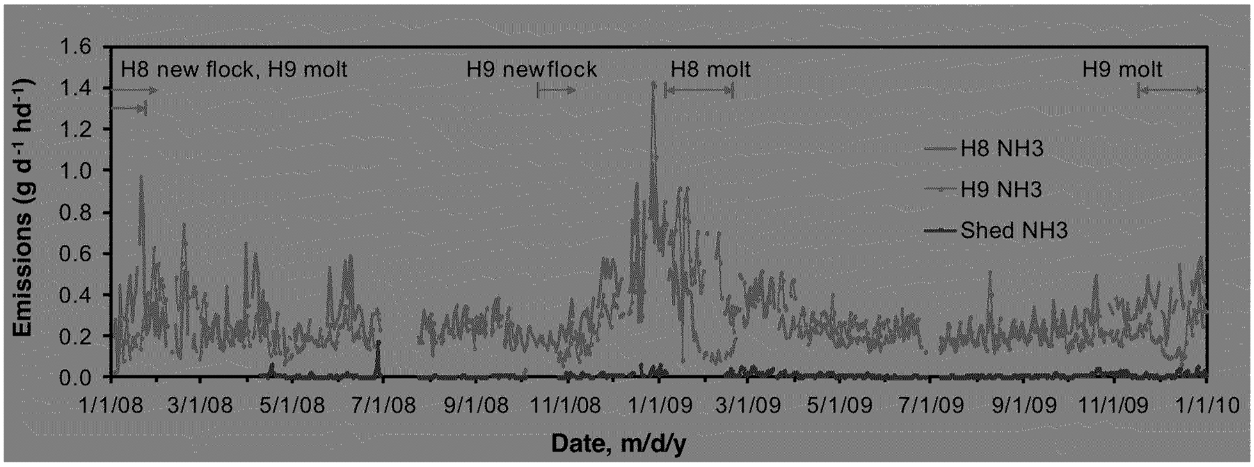

Figure 3.15. Daily means of hen-specific ammonia emissions at IN2B.

The 2-yr ADM NH_3 emissions from H8 and H9, and the shed were 70.6±36.8, 66.5±42.2, and 4.6±6.0 kg/d, respectively (Table 3-103.10). The 2-yr ADM hen-specific NH_3 emissions are listed in Table 3-103.10. House 8 emitted 106.2% of NH_3 compared with H9. However, it was only 101.4% compared with H9 when the emissions were divided by AU. Nonetheless, annual variations between houses were considerable. House 8 emitted 125.8% of NH_3 compared with H9 during the first year monitoring, but only emitted 89.9% of H9 during the second year monitoring. However, statistically, emissions between houses in different units were similar ($P>0.05$).

Hen-specific NH_3 emission rates correlated fairly strongly with indoor house humidity, with r values of 0.351 and 0.490 in houses 8 and 9, respectively (Table 3-103.10). Although inventory was correlated with hen-specific NH_3 emissions in H9, the corresponding correlation in H8 was very weak. No other factor displayed any strong correlation with NH_3 emission from either house.

Table 3-10. Annual and 2-yr statistics of house ammonia emissions from IN2B.

Parameter	H8	H9	Shed	Farm
Total emission				
2-yr valid days, d	624	629	518	476
Minimum DM, kg/d	6.7	0.4	0.1	41.4
Maximum DM, kg/d	263.4	357.1	86.3	647.6
1st yr ADM±SD, kg/d	78.5±42.1	62.4±44.7	4.2±7.6	137.8±85.5
2nd yr ADM±SD, kg/d	63.2±29.4	70.3±39.3	4.9±4.6	129.5±50.8
2-yr ADM±SD, kg/d	70.6±36.8	66.5±42.2	4.6±6	132.9±67.2
Mean±95% c.i., kg/d	70.6±2.9	66.5±3.3	4.6±0.5	132.9±6.0
LM-specific				
2-yr valid days, d	624	609	497	476
Minimum DM, g/d-AU	9.5	6.9	0.1	29.5
Maximum DM, g/d-AU	355.0	492.9	60.6	446.0
1st yr ADM±SD, g/d-AU	106±56.5	91.6±59.6	3.1±5.5	101.6±55.9
2nd yr ADM±SD, g/d-AU	90.9±40.7	101.1±53.2	3.6±3.3	94.6±35.5
2-yr ADM±SD, g/d-AU	98.1±49.5	96.7±56.4	3.4±4.3	97.4±45.0
Mean±95% c.i., g/d-AU	98.1±3.9	96.7±4.5	3.4±0.4	97.4±4.0
Hen-specific				
2-yr valid days, d	624	609	494	476
Minimum DM, g/d-hd	0.03	0.02	0.00	0.08
Maximum DM, g/d-hd	1.04	1.43	0.17	1.29
1st yr ADM±SD, g/d-hen	0.3±0.16	0.27±0.17	0.01±0.02	0.28±0.17
2nd yr ADM±SD, g/d- hen	0.26±0.12	0.29±0.16	0.01±0.01	0.27±0.1
2-yr ADM±SD, g/d- hen	0.28±0.15	0.28±0.16	0.01±0.01	0.27±0.13
Mean±95% c.i., g/d- hen	0.28±0.01	0.28±0.01	0.01±0.00	0.27±0.01

Note: All farm emissions were calculated with (1) DM farm emissions from valid data of all three sources, and (2) 2-yr ADM farm emissions by averaging the DM emissions. The total emissions are the sum of the emissions from two houses and the manure shed. The hen-specific emissions equal the total farm emissions divided by total hens in both houses.

Ammonia emissions were negatively influenced most by inlet temperature, and somewhat by hen age (Table 3-11). Since exhaust RH is inversely related to exhaust temperature (a direct effect), it showed up as a significant positive influence. Other direct positive influences were LMD, and egg production.

Multiple linear regression showed that LMD dominated prediction of hourly mean emissions while exhaust temperature was among the top factors for predicting daily mean emissions followed by egg production and hen age (Table 3-12). Exhaust temperature only appeared as an interaction factor for hourly means at the seventh level, however, its effect was most likely exhibited in the exhaust RH term which was at the top level in the interaction term with LMD.

Table 3-11. Correlations between area-specific NH_3 emission and various factors (*p>0.05).

Parameter	Averaging Interval	r
Exhaust RH	Daily	0.372
Exhaust RH	Hourly	0.293
LMD	Daily	0.230
Inlet RH	Hourly	0.221
LMD	Hourly	0.203
Eggs	Daily	0.146
Static Pressure	Hourly	-0.010*
Atmospheric Pressure	Hourly	-0.019
Ventilation	Hourly	-0.049
Hen Activity	Hourly	-0.060
Solar	Hourly	-0.065
Time of Day	Hourly	-0.082
Exhaust Temp	Hourly	-0.095
Ventilation	Daily	-0.131
Exhaust Temp	Daily	-0.192
Hen Age	Hourly	-0.238
Hen Age	Daily	-0.265
Inlet Temp	Hourly	-0.329
Inlet Temp	Daily	-0.388

Note: n=25282-31400 and 1140-1319 for hourly and daily means, respectively.

Table 3-12. Parameters influencing area-specific ammonia emission.

Hourly Means of NH_3 Emissions		Daily Means of NH_3 Emissions	
Parameter	**r**	**Parameter**	**r**
LMD * Exhaust RH	0.136	Ventilation * Inlet Temp	0.401
LMD	0.600	Ventilation * Exhaust Temp	0.537
Atmospheric Pressure * Inlet Temp	0.634	Inlet Temp * Exhaust RH	0.537
Static Pressure * Inlet Temp	0.636	Eggs * Ventilation	0.575
Hen Activity * Inlet Temp	0.639	House	0.575
LMD * Inlet Temp	0.640	Exhaust Temp	0.592
Exhaust Temp	0.641	Eggs * Hen Age	0.600
Atmospheric Pressure * Exhaust Temp	0.645	Hen Age	0.614
Static Pressure * Exhaust Temp	0.647	Hen Age * Exhaust Temp	0.614
LMD * Exhaust Temp	0.648	Eggs * Exhaust Temp	0.617
Inlet Temp * Exhaust Temp	0.649	Eggs * Exhaust RH	0.618
Exhaust RH	0.650	Eggs* LMD	0.620
Atmospheric Pressure * Hen Activity	0.652	Ventilation * Exhaust RH	0.636
Hen Activity * Exhaust RH	0.652	Inlet Temp * Exhaust Temp	0.643
Static Pressure * Hen Activity	0.654	Ventilation	0.647
Inlet Temp * Exhaust RH	0.655	Inlet Temp	0.649
Inlet Temp	0.658	LMD * Hen Age	0.654
Exhaust Temp * Exhaust RH	0.660	Hen Age * Inlet Temp	0.663
Atmospheric Pressure * LMD	0.661	LMD * Inlet Temp	0.665
Hen Activity	0.662	LMD * Ventilation	0.666
Atmospheric Pressure * Exhaust RH	0.664	Exhaust RH	0.667
House	0.666		
Static Pressure	0.671		
Atmospheric Pressure * Static Pressure	0.673		
Hen Activity * LMD	0.673		
Atmospheric Pressure	0.673		

The predictions using LMD and exhaust temperature resulted in very low R^2 (<10%) (Equations 3.1 and 3.2).

Hourly: $E = -23.28 + 0.501\ D - 0.582\ T \qquad R^2 = 0.05 \qquad (3.1)$

Daily: $E = -3.25 + 0.490\ D - 1.274\ T \qquad R^2 = 0.08 \qquad (3.2)$

3.3.4. Hydrogen Sulfide Concentration and Emission

The daily mean hydrogen sulfide (H_2S) concentrations at the inlets of houses (Figure 3.16) exhibited similar seasonal patterns as NH_3. The house inlet concentrations were high in cold weather and relatively low in warm and hot weather. The seasonal variations of H_2S house exhaust air and manure shed exhaust air are more apparent (Figure 3.17).

The 2-yr ADM inlet H_2S concentrations averaged 1.3±1.7 ppb for H8 and 3.0±4.5 ppb for H9 (Table 3-133.12). These values at house exhausts were 40.0±21.1 ppb for H8 and 41.2±31.5 ppb for H9. The maximum daily mean inlet concentrations were 10 and 35 ppb for H8 and H9, respectively. The maximum daily mean exhaust concentrations were 123 and 211 ppb for H8 and H9, respectively. Annual variations of H_2S concentrations were shown between the two houses. However, H_2S concentrations at the manure shed air exhaust between the first and second year monitoring were negligible.

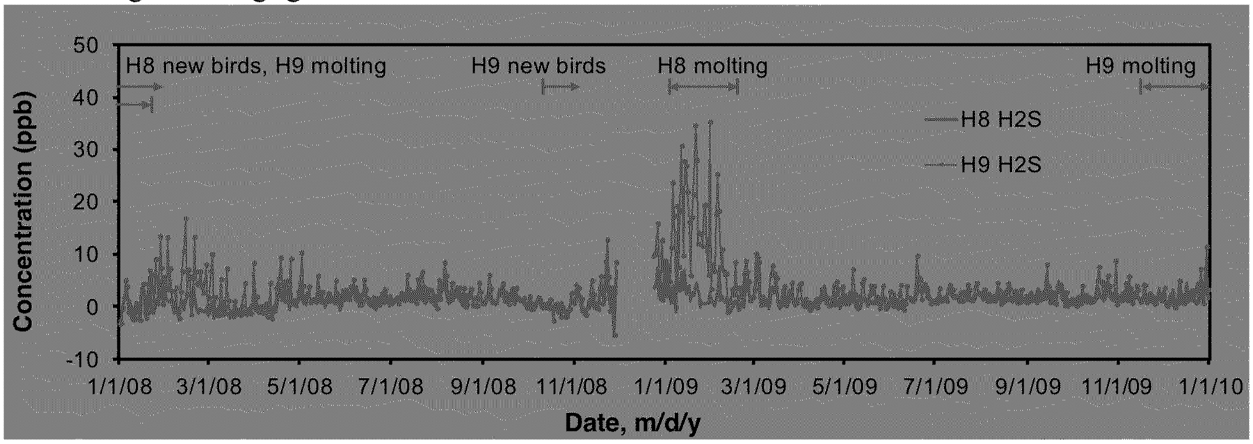

Figure 3.16. Daily means of hydrogen sulfide concentration in house inlets at IN2B.

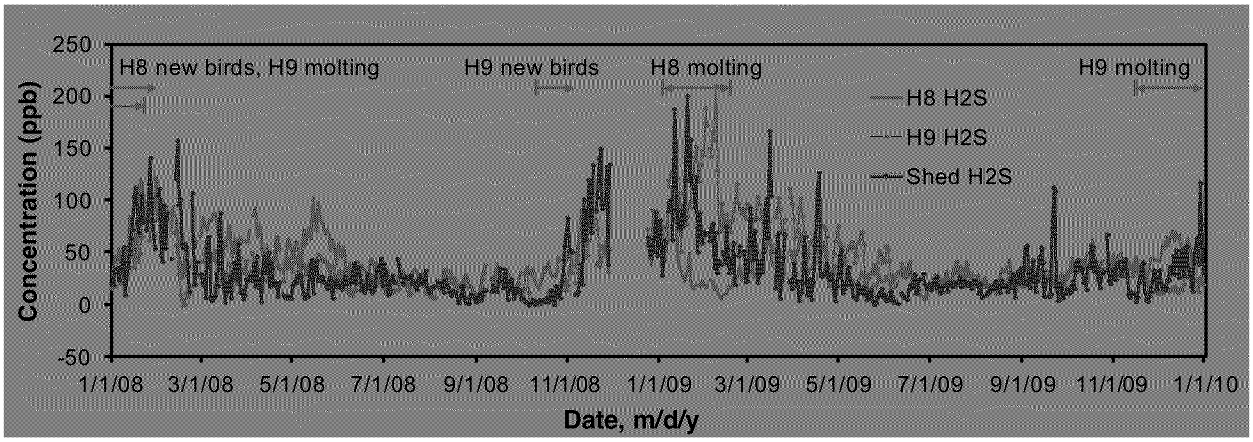

Figure 3.17. Daily means of H_2S concentration at house and shed exhausts.

Table 3-13. Summary of daily mean hydrogen sulfide concentrations (ppb) at IN2B.

Variable	H8 Inlet	H9 Inlet	H8 Exhaust	H9 Exhaust	Shed
2-yr valid days	707	704	679	679	667
Minimum DM	-6	-5	6	0	0
Maximum DM	10	35	123	211	201
1st yr ADM±SD	0.9±1.8	2.2±3.2	47.2±23.7	33.1±22.6	33±31.2
2nd yr ADM±SD	1.7±1.5	3.7±5.3	33.4±15.6	48.6±36.4	34.6±30.8
2-yr ADM±SD	1.3±1.7	3.0±4.5	40.0±21.1	41.2±31.5	33.8±31

No literature on H_2S concentrations in manure belt houses exists. The overall mean exhaust air H_2S concentrations of 19.7 ppb in a high-rise commercial layer house reported by Lim et al. (2003) were considerably lower than the levels encountered here. However, the 40 – 100 ppb H_2S concentrations detected by Zhu et al. (2000) in a broiler house were higher than this study.

The seasonal fluctuations of H_2S emissions did not show a clear pattern in the two houses and the manure shed (Figure 3.18) as compared with NH_3 emissions. This indicated that, although H_2S concentrations were higher in winter, the H_2S production inside the houses and the manure shed were not necessarily affected by ventilation rate and manure moisture content. As with NH_3 concentrations, molting of hens also reduced H_2S concentrations in H8. Previous research showed that the release of H_2S were more unpredictable compared with other gases commonly found in animal wastes. Because of the relatively constant live mass density except for empty days between flocks, the seasonal patterns of LM- and hen-specific H_2S emissions (Figure 3.19 and Figure 3.20) remained similar to the total emissions from both houses.

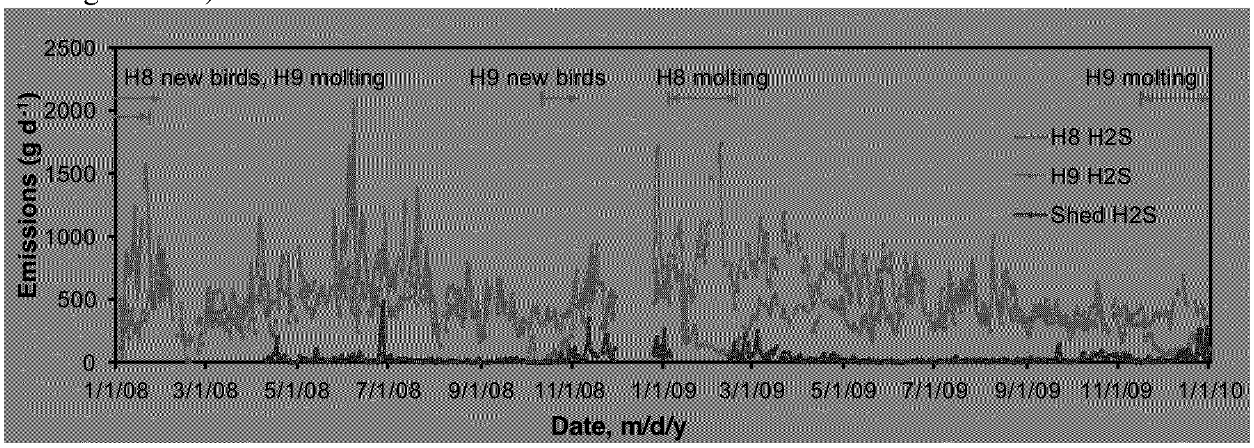

Figure 3.18. Daily means of H_2S emissions from both houses and the manure shed.

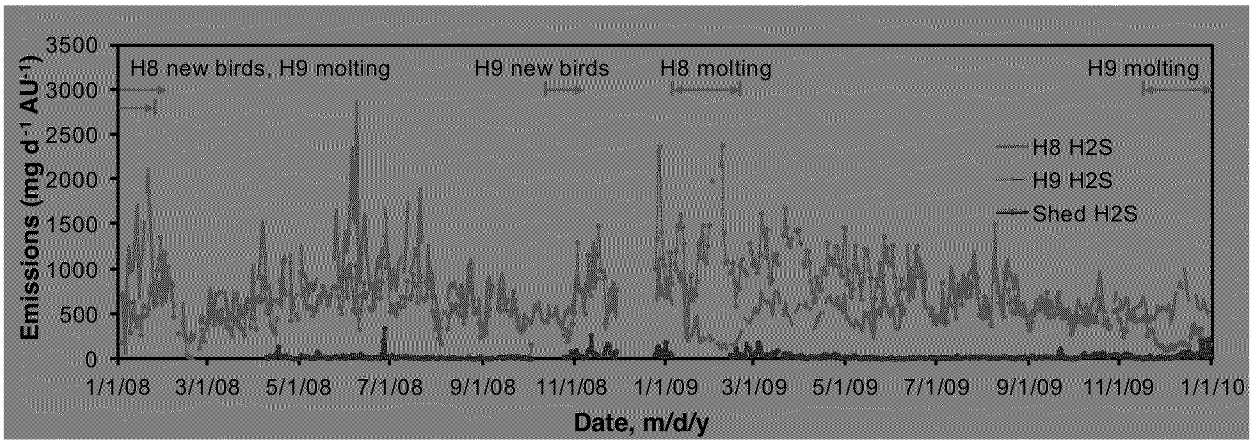

Figure 3.19. Daily means of LM-specific H_2S emissions from houses and manure shed.

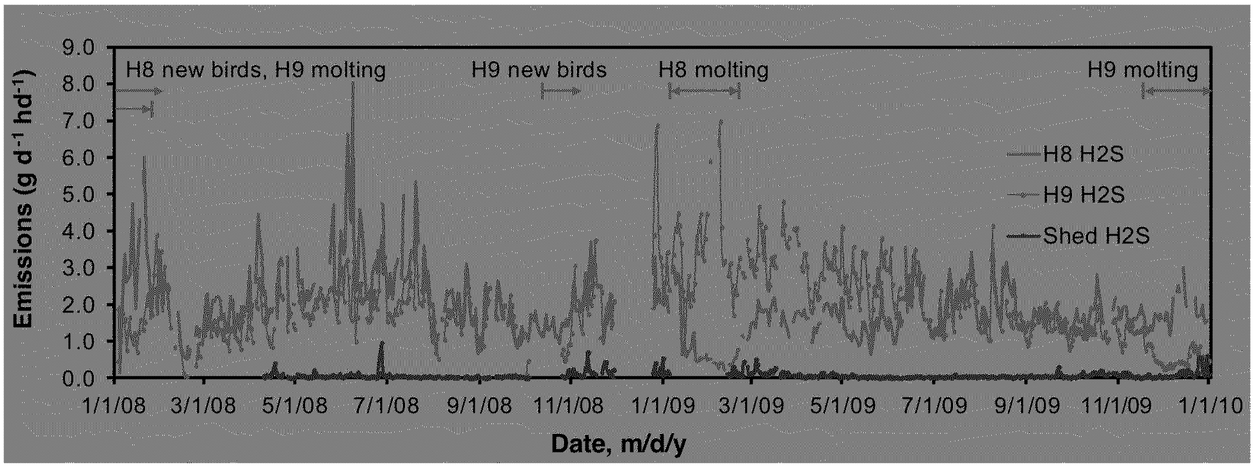

Figure 3.20. Daily means of hen-specific hydrogen sulfide emissions from houses and manure shed.

The 2-yr ADM H_2S emissions from H8, H9, and manure shed were 489±241, 469±265, and 35±48 g/d, respectively (Table 3-143.13). The 2-yr ADM LM-specific emissions from H8 and H9, and the manure shed were 679±324, 685±359 and 26±35 mg/d-AU, respectively. Emissions from the manure shed were about 3.75% of those emitted from the houses. Annual emission variations and house emission variations were profound. First year emissions from H8 were 48% higher than the second year, while those from H9 were 19% lower. However, variations between the houses resulted in more similar emission rates, in which H8 was only 4% higher than H9.

Table 3-14. Summary of daily mean hydrogen sulfide emissions.

Parameter	H8, g/d	H9, g/d	Shed, g/d	H8, mg/d-AU	H9, mg/d-AU	Shed, mg/d-AU
2-yr valid days	634	645	534	634	624	513
Minimum DM	41	-37	-1	59	-49	0
Maximum DM	2090	1740	483	2864	2381	339
1st yr ADM±SD	589±279	418±232	35±55	797±380	621±305	27±41
2nd yr ADM±SD	399±152	516±284	35±42	572±214	740±391	25±31
2-yr ADM±SD	489±241	469±265	35±48	679±324	685±359	26±35

Correlations between hen-specific H_2S emissions and various house factors were inconsistent (Table 3.14). The only factor with $r>0.2$ in both houses was inventory, with $r>0.243$ in H8 and 0.331 in H9.

Hydrogen sulfide emissions were positively correlated with egg production, ventilation rate, and live mass density, and negatively correlated with hen age according to the single factor analysis (Table 3-15).

Table 3-15. Correlations between area-specific H_2S emissions and various factors (*p>0.05).

Parameter	Averaging Interval	r
Eggs	Daily	0.348
Ventilation	Hourly	0.218
LMD	Daily	0.210
Ventilation	Daily	0.208
LMD	Hourly	0.185
Exhaust RH	Daily	0.175
Exhaust Temp	Hourly	0.150
Exhaust RH	Hourly	0.114
Inlet Temp	Hourly	0.093
Solar	Hourly	0.087
Exhaust Temp	Daily	0.083
Inlet Temp	Daily	0.067
Hen Activity	Hourly	0.019
Time of Day	Hourly	0.016
Inlet RH	Hourly	0.005*
Static Pressure	Hourly	-0.082
Atmospheric Pressure	Hourly	-0.104
Hen Age	Hourly	-0.367
Hen Age	Daily	-0.407

Note: n=24860-31400 and 1111-1344 for hourly and daily means, respectively.

Multiple linear regression showed that LMD and exhaust temperature interactively accounted for most of the variance in hourly means while egg production and exhaust RH interactively accounted for most of the variance in daily means (Table 3-16). Both flock and thermal characteristics collectively were correlated to greater H_2S emissions.

Table 3-16. Parameters influencing area-specific H_2S emission.

Hourly Means of H_2S Emissions		Daily Means of H_2S Emissions	
Parameter	**r**	**Parameter**	**r**
LMD * Exhaust Temp	0.296	Eggs * Exhaust RH	0.211
Exhaust RH	0.346	Hen Age * Exhaust RH	0.297
Inlet RH	0.517	Ventilation * Exhaust RH	0.349
Time of Day * LMD	0.544	Ventilation * Inlet Temp	0.364
Hen Activity * LMD	0.547	Ventilation * Exhaust Temp	0.401
Hen Activity * Hen Age	0.548	Ventilation	0.435
LMD * Hen Age	0.550	Exhaust Temp	0.456
Inlet Temp	0.551	House	0.460
Hen Activity	0.552	Hen Age * Exhaust Temp	0.472
Time of Day * Inlet Temp	0.552	Eggs * Exhaust Temp	0.483
Hen Activity * Inlet Temp	0.554	Eggs * Hen Age	0.499
LMD * Inlet Temp	0.557	Exhaust Temp * Exhaust RH	0.505
LMD	0.561	Eggs * Ventilation	0.511
Hen Activity * Exhaust Temp	0.561	Hen Age * Ventilation	0.522
Hen Age * Inlet Temp	0.564	Exhaust RH	0.525
Time of Day * Inlet RH	0.564	Eggs * LMD	0.526
House	0.564	LMD * Exhaust Temp	0.540
Hen Activity * Inlet RH	0.564	Hen Age	0.542
LMD * Inlet RH	0.564	LMD * Ventilation	0.542
Hen Age * Inlet RH	0.565	LMD * Inlet Temp	0.546
Inlet Temp * Inlet RH	0.567	Inlet Temp * Exhaust Temp	0.550
Exhaust Temp	0.570	Inlet Temp * Exhaust RH	0.550
Time of Day * Exhaust Temp	0.570		
Inlet Temp * Exhaust Temp	0.571		
Time of Day * Hen Activity	0.572		
Inlet RH * Exhaust Temp	0.572		
Time of Day * Exhaust RH	0.576		
Hen Activity * Exhaust RH	0.576		
LMD * Exhaust RH	0.576		
Hen Age * Exhaust RH	0.577		
Inlet Temp * Exhaust RH	0.577		
Inlet RH * Exhaust RH	0.577		
Exhaust Temp * Exhaust RH	0.577		
Hen Age	0.582		
Time of Day	0.583		

Exhaust temperature and LMD accounted for only 6 and 5% of the hourly and daily mean H_2S emissions, respectively (Equations 3.3 and 3.4).

Hourly: $E = -433 + 3.15\ D + 7.61\ T$, $R^2 = 0.06$ (3.3)

Daily: $E = -351 + 3.16\ D + 4.65\ T$, $R^2 = 0.05$ (3.4)

3.3.5. Carbon Dioxide Concentration and Emission

The daily mean inlet CO_2 concentration, sampled in the attics, were generally higher (up to 600 to 700 ppm) in the cold months and lower in the warm months (400 to 500 ppm) (Figure 3.21). This seasonal patterns agreed very well with the patterns of NH_3 and H_2S concentrations. It also showed agreement with house exhaust CO_2 concentrations (Figure 3.22). The correlation between inlet and exhaust suggested that gas concentrations in house air inlets were affected by exhaust concentrations.

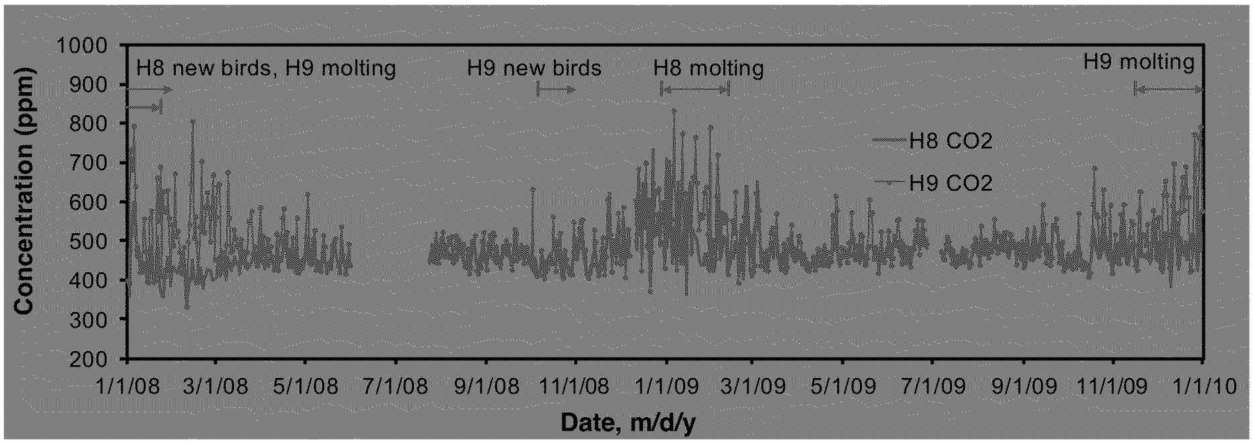

Figure 3.21. Daily means of carbon dioxide concentration at inlets.

The exhaust CO_2 concentrations were similar between houses (Figure 3.22). The 2-yr ADM concentrations were 2295±871 ppm in H8, and 2285±946 in H9. The patterns of seasonal CO_2 concentration variations were very similar to those of NH_3. The highest daily mean concentrations were detected between January and March. The highest daily mean CO_2 concentrations were 4970 and 4660 ppm for houses 8 and 9, respectively (Table 3-153.15). July and August were the months of lowest CO_2 concentrations. The exceptionally low CO_2 concentrations in H9 at the end of October, 2008 were due to empty house days between two flocks of hens. Because the exhaust gas concentrations were sampled at the inlets of selected ventilation fans, which were only 1 m away from the cages, these data also represented CO_2 concentrations in the living area of the hens. However, CO_2 concentrations at the manure shed exhaust did not exhibit seasonal variations (Figure 3.22). They were relatively stable all year round because manure shed was free of CO_2 sources from hen respiration and there were no seasonal variations of ventilation rates.

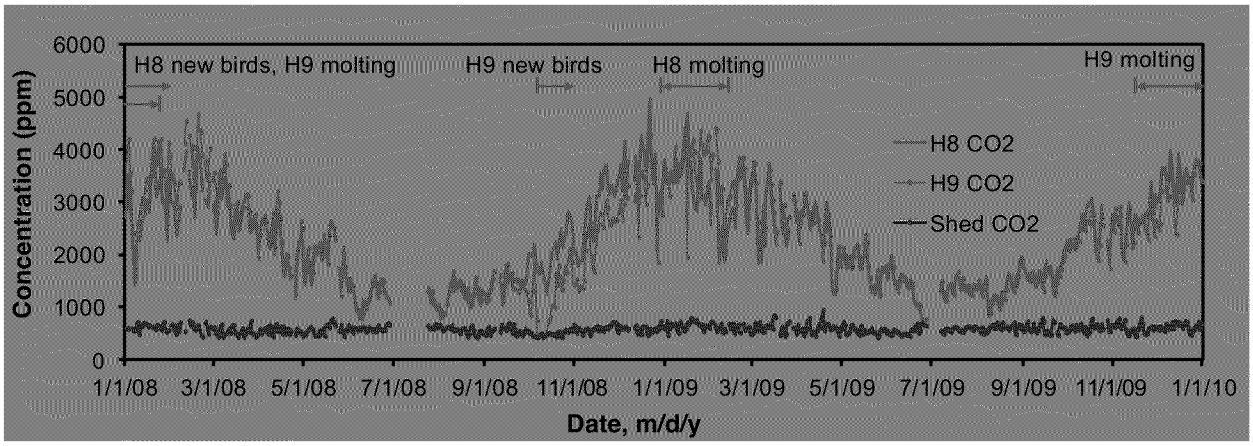

Figure 3.22. Daily means of carbon dioxide concentration at house exhausts.

Table 3-15. Summary of daily mean carbon dioxide concentrations in ppm at IN2B.

Parameter	H8 Inlet	H9 Inlet	H8 Exhaust	H9 Exhaust	Shed
2-yr valid days	666	662	666	666	656
Minimum DM	334	332	747	418	413
Maximum DM	732	833	4972	4663	931
1st yr ADM±SD	456±47	493±72	2258±898	2222±993	557±74
2nd yr ADM±SD	478±43	503±73	2330±843	2344±896	590±82
2-yr ADM±SD	468±46	498±73	2295±871	2285±946	574±80

The layer hen house CO_2 concentrations differed from some reported values. A recent survey of seven laying hen houses in Slovenia resulted in mean CO_2 concentrations of 758 ppm in exhaust air (Dobeic and Pintaric, 2011). In a study in Iowa with 24-h measurements, the mean CO_2 concentrations were 3072 ppm in winter and 1012 ppm in summer in four belt houses. In four high-rise houses, the mean CO_2 concentrations were 2433 and 520 ppm in winter and summer, respectively (Green et al., 2009).

High CO_2 concentrations have a negative health effect on layer hens. In a laboratory chamber study, Helbacka et al. (1963) showed that exposure of layer hens to 5% CO_2 concentration caused a drop in blood pH and reduction in shell thickness. However, the 5% CO_2 is about 10 times as high as the maximum daily mean concentration in H8. Whether CO_2 at about 5000 ppm has negative effects on layer hen health is still unknown and needs more investigation.

Emissions of CO_2 from both houses exhibited similar seasonal patterns as NH_3 emissions. During empty days between flocks in H9, the CO_2 emission decreased to zero (Figure 3.23). The peaks of CO_2 emissions occurred in winter. This was probably due to greater metabolism of the hens when the indoor temperatures were relatively lower than summer and that wet manure produced more CO_2 (Ni et al., 2010). Figure 3.24 presents daily mean LM-specific CO_2 emissions.

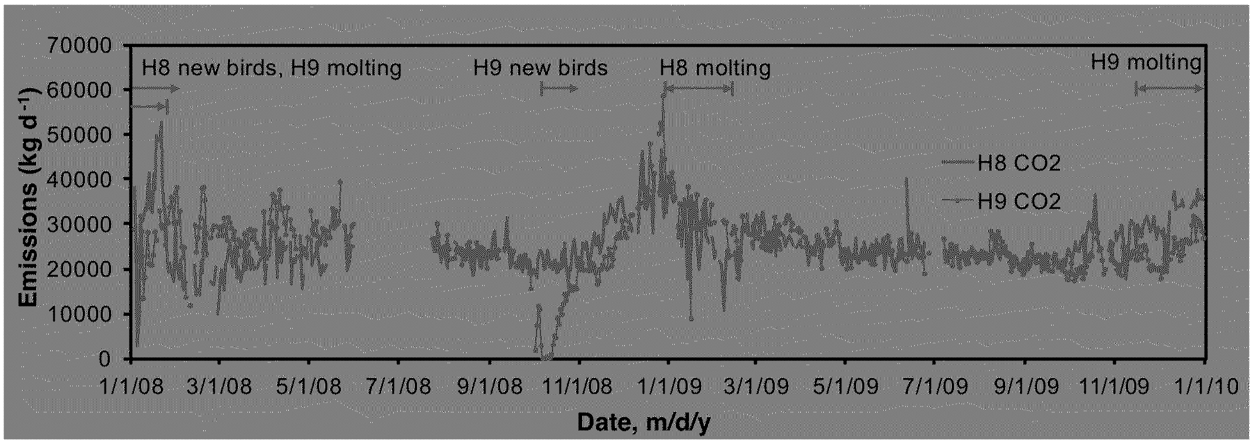

Figure 3.23. Daily means of carbon dioxide emission rate per house.

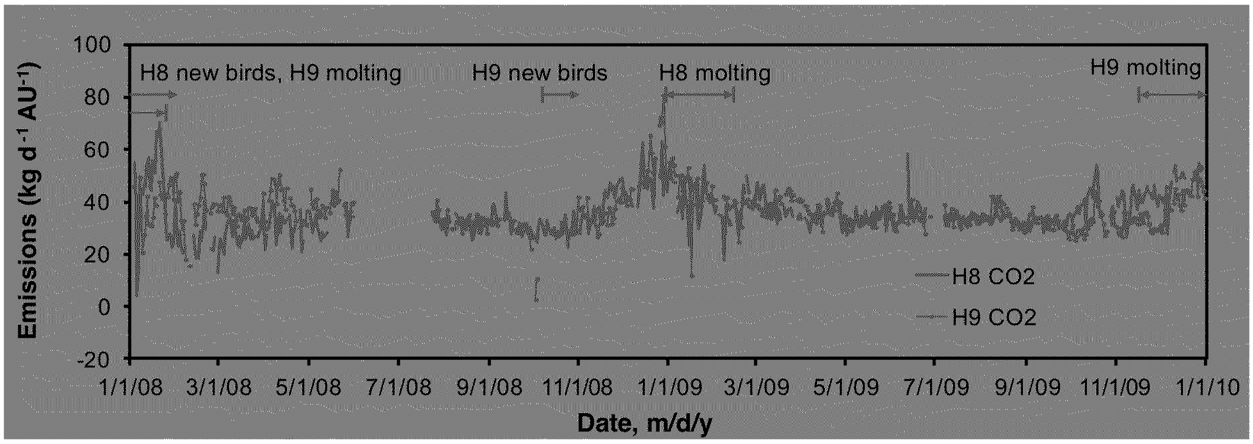

Figure 3.24. Daily means of LM-specific carbon dioxide emission rate.

The quantities of CO_2 emissions from the houses were 25,316±5,659 kg/d for H8 and 25,140±6,717 kg/d for H9 (Table 3-163.16). Compared with the houses, the manure shed CO_2 emission was only 87±153 kg/d. The 2-yr ADM LM-specific CO_2 emissions were similar between houses. They were 35.5±8.1 and 36.8±7.4 kg/d from houses 8 and 9, respectively.

Table 3-16. Summary of daily mean carbon dioxide emissions at IN2B.

Parameter	H8, kg/d	H9, kg/d	Shed, kg/d	H8, kg/d-AU	H9, kg/d-AU	Shed, kg/d-AU
2-yr valid days	598	606	489	598	585	468
Minimum DM	3001	-287	-786	4	3	-532
Maximum DM	52785	58796	706	70	81	526
1st yr ADM±SD	24845±6870	25479±8718	69±154	33.6±9.4	37.7±8.8	54±111
2nd yr ADM±SD	25709±4361	24857±4373	98±151	37.1±6.3	36.2±6	71±110
2-yr ADM±SD	25316±5659	25140±6717	87±153	35.5±8.1	36.8±7.4	65±110

Emissions were obviously diurnally related since indirect effects solar radiation and ventilation rate were top factors (Table 3-19). This table shows conclusively that CO_2 emissions decreased with temperature and increased with flock inventory.

Table 3-19. Correlations between area-specific CO_2 emission and various factors (*p>0.05).

Parameter	Averaging Interval	r
Exhaust RH	Daily	0.197
LMD	Daily	0.151
Solar	Hourly	0.148
Ventilation	Hourly	0.142
LMD	Hourly	0.105
Time of Day	Hourly	0.075
Hen Activity	Hourly	0.073
Exhaust Temp	Hourly	0.069
Exhaust RH	Hourly	0.029
Atmospheric Pressure	Hourly	0.019
Eggs	Daily	0.007
Inlet RH	Hourly	-0.005*
Hen Age	Hourly	-0.020
Hen Age	Daily	-0.029*
Ventilation	Daily	-0.066
Static Pressure	Hourly	-0.125
Exhaust Temp	Daily	-0.156
Inlet Temp	Hourly	-0.199
Inlet Temp	Daily	-0.366

Note: n=26049-32064 and 1090-1319 for hourly and daily means, respectively.

The multiple linear regression showed inlet and exhaust temperatures with their associated variables having a predominant role in accounting for the variation in CO_2 emissions (Table 3-20). The house effect was significant but was not among the top five factors. The top flock factor was hen activity for hourly means and egg production for daily means.

Table 3-20. Parameters influencing area-specific carbon dioxide emissions.

Hourly Means of CO_2 Emissions		Daily Means of CO_2 Emissions	
Parameter	**r**	**Parameter**	**r**
Inlet Temp * Inlet RH	0.122	Ventilation * Inlet Temp	0.41
Ventilation * Inlet Temp	0.523	Ventilation * Exhaust Temp	0.577
Inlet Temp * Exhaust RH	0.851	Eggs * Exhaust Temp	0.478
Hen Activity * Ventilation	0.855	Exhaust Temp	0.579
Static Pressure * Hen Activity	0.859	Inlet Temp * Exhaust RH	0.079
Solar * Inlet Temp	0.859	House	0.079
Hen Age	0.862	Ventilation	0.479
Hen Activity * Hen Age	0.862	Ventilation * Exhaust RH	0.879
Atmospheric Pressure * Hen Age	0.863	Hen Age	0.880
Static Pressure * Hen Age	0.866	LMD * Ventilation	0.080
LMD * Exhaust RH	0.866	Eggs * Inlet Temp	0.280
Solar * Hen Activity	0.868	Hen Age * Exhaust RH	0.681
Solar * Ventilation	0.869	LMD * Exhaust RH	0.381
Atmospheric Pressure * Ventilation	0.870	LMD * Inlet Temp	0.581
Inlet Temp	0.870		5
Ventilation	0.870		
Atmospheric Pressure * Inlet Temp	0.871		
House	0.871		
Static Pressure * Ventilation	0.871		
Solar * Hen Age	0.872		
Inlet RH	0.872		
Solar * Inlet RH	0.873		
Time of Day * Hen Age	0.873		
Hen Age * Inlet Temp	0.875		
Static Pressure * Inlet Temp	0.875		
Static Pressure * Exhaust RH	0.875		
Hen Age * Inlet RH	0.876		
Atmospheric Pressure * Static Pressure	0.876		
Atmospheric Pressure * Exhaust RH	0.876		
Ventilation * Inlet RH	0.876		
Hen Activity * Exhaust RH	0.877		
Atmospheric Pressure * Hen Activity	0.877		
Exhaust RH	0.877		
Hen Activity	0.877		
Static Pressure	0.877		
Solar * Static Pressure	0.878		
Hen Activity * Inlet RH	0.878		
Hen Age * Exhaust RH	0.878		
Atmospheric Pressure * Inlet RH	0.878		
Solar	0.879		
Atmospheric Pressure	0.879		

Exhaust temperature and LMD fared poorly in predicting CO_2 for both hourly and daily means (Equations 3.5 and 3.6).

Hourly:	$E = 81.1 + 49.94\ D + 105.05\ T,$	$R^2 = 0.02$	(3.5)
Daily:	$E = 7691 + 44.38\ D - 151.35\ T$	$R^2 = 0.04$	(3.6)

3.3.6. Correlations among Gaseous Pollutants

Emissions of NH_3 and CO_2 were strongly correlated in both houses, with r values slightly over 0.7 (Table 3-213.18). This would be expected, as both gases are produced under similar (aerobic) conditions. Interestingly, however, the two did not correlate at all in the manure shed. The H_2S emission correlated significantly with CO_2 and NH_3 in both houses, and very strongly ($r = 0.837$) with NH_3 in the manure shed. PM_{10} correlations with all gases were weak in both houses and in the shed, with the exception of negative correlation ($r = -0.261$) with CO_2 emissions in the latter.

Table 3-21. Correlations between daily emission rates of four pollutants.

	NH_3	**H_2S**	**CO_2**
House 8*			
NH_3	-	-	-
H_2S	0.450	-	-
CO_2	0.708	0.352	-
PM_{10}	0.059	0.055	0.093
House 9*			
NH_3	-	-	-
H_2S	0.572	-	-
CO_2	0.702	0.430	-
PM_{10}	-0.044	0.001	-0.181
Shed*			
NH_3	-	-	-
H_2S	0.837	-	-
CO_2	-0.010	-0.072	-
PM_{10}	0.048	0.021	-0.261

* Hen-specific emission rates for H8 and H9, and whole-building rates for the manure shed.

3.3.7. PM_{10} Concentration and Emission

The daily mean PM_{10} concentrations at the house air exhausts varied considerably between the houses (Figure 3.25). The daily mean inlet and the manure shed PM_{10} concentrations (Figure 3.26) were generally much lower than the house exhausts. However, although not shown in the daily mean data plots, PM_{10} concentrations in the manure shed were very high while manure moved to the manure shed via conveyers. The manure movement occurred from Monday to Saturday in the morning for about 3 to 4 h. High concentrations of PM in the manure shed were also detected when loading the manure in the shed onto trucks. Unlike gases, it was difficult to correlate the PM_{10} concentrations to seasonal temperature variations.

An interesting weekly variation of PM_{10} concentrations was exhibited. This phenomenon was the most visible for H9. Data analysis confirmed that the PM_{10} concentrations in the belt house were the lowest on Sundays. From April to November, 2008 and from March to December, 2009, PM_{10} concentrations on Sundays were mostly <100 μg/m^3. This special characteristic of PM_{10} concentrations was related to house operational activities. Sunday was the only day during the week that farm workers did not perform routine tasks, including operations of the manure-belt and manure conveyers that transported manure to the manure shed in the morning.

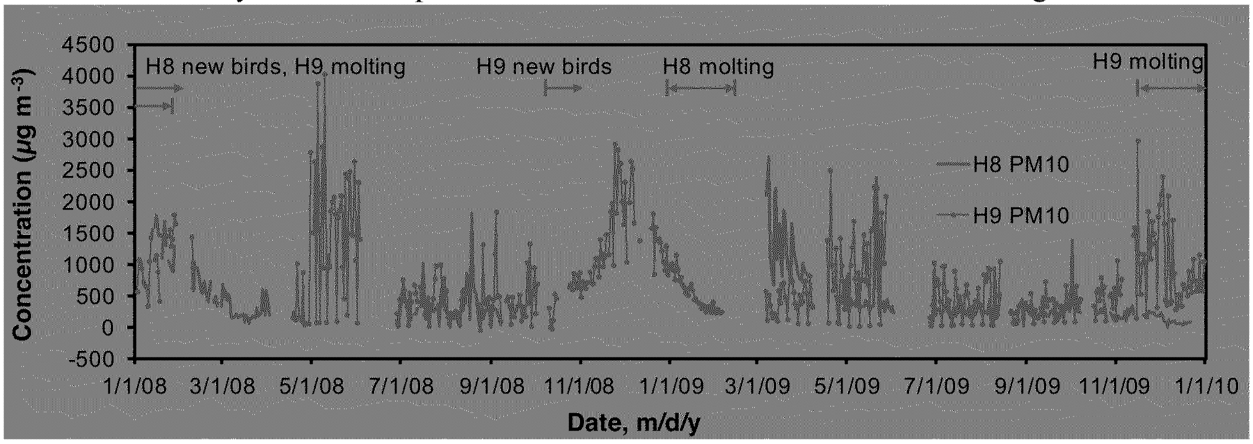

Figure 3.25. Daily means of PM_{10} concentrations at houses 8 and 9 exhausts at IN2B.

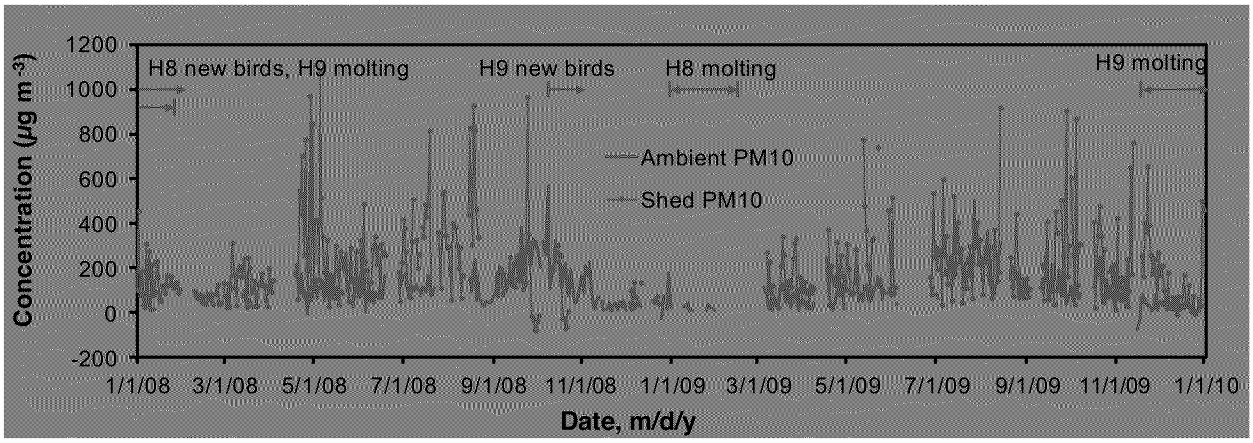

Figure 3.26. Daily means of ambient and manure shed PM_{10} concentrations at IN2B.

Because the PM measurement instruments (TEOM) were more susceptible to errors and failures, data completeness for PM_{10} measurements were lower than gas concentrations. At the four main monitoring locations (Table 3-223.19), valid days ranged from 362 to 474 d. The 2-yr ADM PM_{10} concentration differed between the two houses. House 8 had only 76.4% of that in H9. The maximum daily mean concentrations were also lower in H8 (2702 μg/m^3) than in H9 (4039 μg/m^3). The distribution of valid days in Figure 3.25 shows that missing data affected 2-yr ADM concentrations in H8 more than in H9. Therefore, concentrations in H9 were more representative.

Table 3-22. Mean (±SD) of PM_{10} concentrations at IN2B.

Parameter	Ambient, $\mu g/m^3$	H8 Exh., $\mu g/m^3$	H9 Exh., $\mu g/m^3$	Shed, $\mu g/m^3$	H8/H9 Exh., %
2-yr valid days	458	362	474	458	76.4
Minimum DM	-74	-11	-45	-77	25.3
Maximum DM	567	2702	4039	1083	66.9
1st yr ADM±SD	113±84	438±393	929±778	205±193	47.1
2nd yr ADM±SD	104±80	402±447	629±516	210±172	63.9
2-yr ADM±SD	108±82	415±428	761±661	207±183	54.5

The 2-yr ADM PM_{10} concentrations were in the lower end of the range reported by Ellen et al. (2000), and closer to the 0.84 mg/m^3 respirable particle concentrations obtained in a survey by Banhazi et al. (2008).

House-specific emissions of PM_{10} from the entire houses (Figure 3.27), as well as LM-specific emissions (Figure 3.28) and hen-specific emissions (Figure 3.29) could not be correlated to seasonal temperature variations. The patterns of the daily PM_{10} emissions appeared random. The maximum emissions occurred between April and May, 2008 from H9. The 2-yr ADM emissions from houses 8 and 9 were 3086±4812 and 6076±8226 g/d, respectively (Table 3-233.20). House 8 emitted only 64.1% of PM_{10} as H9. However, the difference was not statistically significant due to high variations. The 2-yr ADM emission from the manure shed was 134±293 g/d. Table 3-243.21 lists LM- and hen-specific PM_{10} emissions. When combining the emissions from the houses and the manure shed, the 2-yr ADM emissions were 6.65 g/d-AU and 19.0 mg/d-hen for the farm.

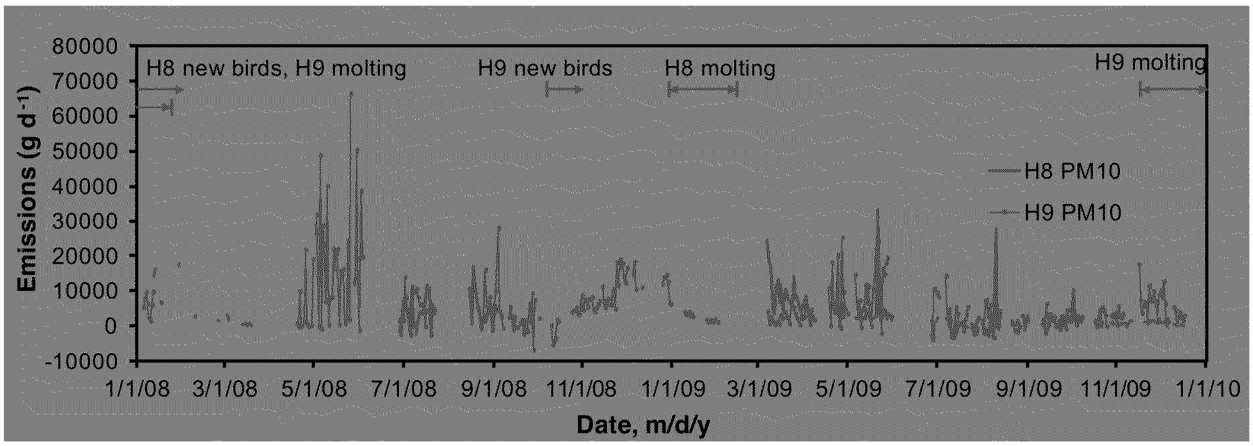

Figure 3.27. Daily means of PM_{10} emissions per house at IN2B.

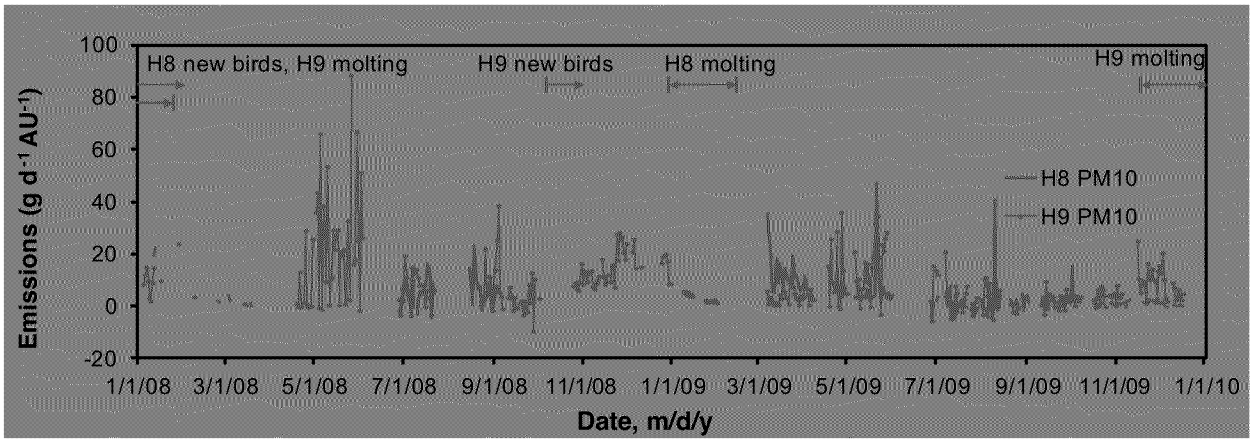

Figure 3.28. Daily means of PM_{10} emissions per animal unit from both houses.

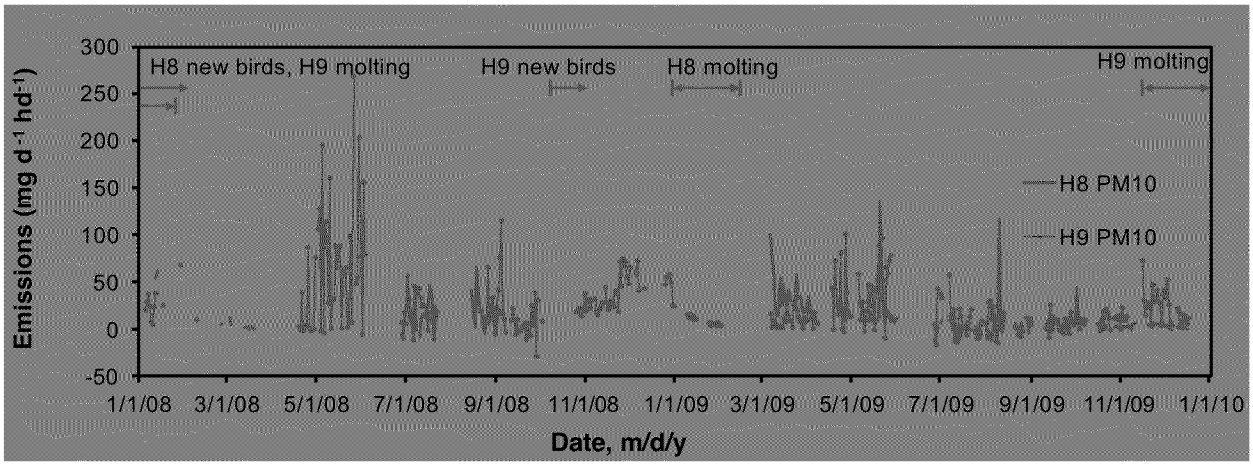

Figure 3.29. Daily means of hen-specific PM_{10} emissions from both houses at IN2B.

Table 3-23. Mean (±SD) of PM_{10} house emissions in g/d at IN2B.

Parameter	H8	H9	Shed
2-yr valid days	248	361	307
Minimum DM	-3474	-6845	-358
Maximum DM	33225	66503	2557
1st yr ADM±SD	4059±4781	8568±10437	144±352
2nd yr ADM±SD	2789±4783	4093±5094	127±247
2-yr ADM±SD	3086±4812	6076±8226	134±293

Table 3-24. Mean (±SD) of PM_{10} emissions per AU and per head at IN2B.

Parameter	Per AU, g/d-AU			Per hen, mg/d-hen		
	H8	H9	Shed	H8	H9	Shed
2-yr valid days	248	354	298	248	354	298
Minimum DM	-5	-10	0	-14	-29	-1
Maximum DM	47	89	2	136	269	5
1st yr ADM±SD	5.5±6.5	12.7±14.1	0.1±0.2	15.66±18.41	36.4±42.2	0.3±0.7
2nd yr ADM±SD	3.9±6.8	6±7.4	0.1±0.2	11.4±19.47	16.7±20.7	0.3±0.5
2-yr ADM±SD	4.3±6.7	8.9±11.3	0.1±0.2	12.4±19.31	25.2±33.3	0.3±0.6

Hen-specific PM_{10} emission rates showed some correlation with inventory (Table 3.22). The most likely explanation for this would seem to be that hens are more active when first introduced, which would correspond to periods of maximum inventory, and that activity (which generates dust) decreases as hens get older.

PM_{10} emissions were positively correlated with LMD and hen activity, and negatively related to hen age and exhaust temperature (Table 3-25). The amount of variance these factors accounted were relatively low, however, it makes sense that more hens and their activity increase dust emissions and that the activity of the hens decrease with age and temperature.

Table 3-25. Correlations between area-specific PM_{10} emissions and various factors (*p>0.05).

Parameter	Averaging Interval	r
LMD	Daily	0.193
Hen Activity	Hourly	0.114
Solar	Hourly	0.087
Exhaust RH	Hourly	0.069
Inlet RH	Hourly	0.037
LMD	Hourly	0.036
Ventilation	Daily	0.016 *
Atmospheric Pressure	Hourly	-0.008*
Exhaust Temp	Hourly	-0.019
Ventilation	Hourly	-0.019
Inlet Temp	Hourly	-0.019
Hen Age	Hourly	-0.029
Inlet Temp	Daily	-0.033*
Eggs	Daily	-0.054*
Exhaust RH	Daily	-0.062*
Time of Day	Hourly	-0.096
Exhaust Temp	Daily	-0.102
Hen Age	Daily	-0.118
Static Pressure	Hourly	-0.160

Note: n=26012-31343 and 581-1319 for hourly and daily means, respectively.

Multiple linear regression showed significant differences between houses for daily means. The diurnal patterns caused high correlations with other diurnally variation parameters such as time of day, solar radiation, static pressure, and hen activity (Table 3-26). Overall, the top flock factors were hen LMD, activity, age and egg production. Egg production was not included in hourly mean analysis.

Table 3-26. Factors influencing hourly mean area-specific PM_{10} emissions.

Hourly Means of PM_{10} Emissions		Daily Means of PM_{10} Emissions	
Parameter	**r**	**Parameter**	**r**
Time of Day * Solar	0.065	House	0.046
Solar	0.095	LMD	0.094
Static Pressure * Hen Activity	0.100	Eggs * Exhaust RH	0.150
Time of Day * Hen Activity	0.103	Hen Age	0.167
Static Pressure * Hen Age	0.105	LMD * Hen Age	0.176
Time of Day * Hen Age	0.108	LMD	0.177
LMD * Hen Age	0.112		
Hen Activity * Ventilation	0.113		
Ventilation * Inlet Temp	0.117		
Ventilation * Exhaust Temp	0.125		
Hen Age * Inlet Temp	0.128		
Hen Age * Exhaust Temp	0.129		
Static Pressure * LMD	0.131		
Ventilation	0.133		
Time of Day * Ventilation	0.135		
Solar * Hen Activity	0.136		
LMD * Exhaust RH	0.140		
Inlet Temp	0.141		
Atmospheric Pressure * Hen Activity	0.141		
Time of Day * Inlet Temp	0.141		
Solar * Inlet Temp	0.142		
Atmospheric Pressure * Inlet Temp	0.142		
Static Pressure * Inlet Temp	0.143		
Solar * Static Pressure	0.145		
LMD * Ventilation	0.145		
Static Pressure	0.146		
Hen Activity * Inlet RH	0.146		
Hen Activity * Hen Age	0.147		
Exhaust Temp	0.147		
Solar * Exhaust Temp	0.147		
Hen Activity * Exhaust Temp	0.147		
Hen Activity * Inlet Temp	0.147		
Inlet RH * Exhaust Temp	0.147		
Inlet RH	0.148		
Hen Activity * Exhaust RH	0.148		
Atmospheric Pressure * Hen Age	0.149		
Hen Age * Exhaust RH	0.149		
Solar * Ventilation	0.150		
Ventilation * Exhaust RH	0.152		
Inlet Temp * Exhaust RH	0.152		
Inlet RH * Exhaust RH	0.152		

Exhaust temperature and LMD accounted for only 0.2 and 6% of the hourly and daily mean PM_{10} emissions, respectively (Equations 3.7 and 3.8).

Hourly:	$E = 1812 + 40.240\ D - 67.490\ T$	$R^2 = 0.002$	(3.7)
Daily:	$E = -5795 + 104.060\ D - 207.625\ T$	$R^2 = 0.06$	(3.8)

3.3.8. $PM_{2.5}$ Concentration and Emission

Valid days for $PM_{2.5}$ ranged from 25 in H8 and 37 in the ambient air (Table 3-173.23 and Figure 3.30). House 8 had only measurement data in 2009 due to an instrument problem during the measurement in 2008. The ambient daily mean $PM_{2.5}$ concentrations ranged from 0.9 to 142 $\mu g/m^3$. The 2-yr ADM ambient concentration was 33.2±41.4 (average ±SD) $\mu g/m^3$. The 2-yr ADM house exhaust concentrations were 36.1±86.8 $\mu g/m^3$ for H8 and 5.9±30.7 $\mu g/m^3$ for H9, while that for the shed was 25.1±20.7 $\mu g/m^3$. The concentrations between the houses and between the houses and the shed were all statistically different (P>0.05). Negative concentrations were due to interferences of moisture content in the air samples.

Table 3-17. Mean (±SD) of house inlet and exhaust $PM_{2.5}$ concentrations at IN2B.

Parameter	Ambient, $\mu g/m^3$	H8 Exh., $\mu g/m^3$	H9 Exh., $\mu g/m^3$	Shed, $\mu g/m^3$	H8/H9 Exh., %
2-yr valid days	37	25	31	30	80.6
Minimum DM	0.9	-36.9	-33.8	1.8	109.2
Maximum DM	142.0	242.8	74.4	108.9	326.4
1st yr ADM±SD	74.2±50.5		42.2±25.4	45.9±36.5	
2nd yr ADM±SD	25.2±34.1	36.1±86.8	-2.8±24.8	19.9±8.4	-1289
2-yr ADM±SD	33.2±41.4	36.1±86.8	5.9±30.7	25.1±20.7	611.9

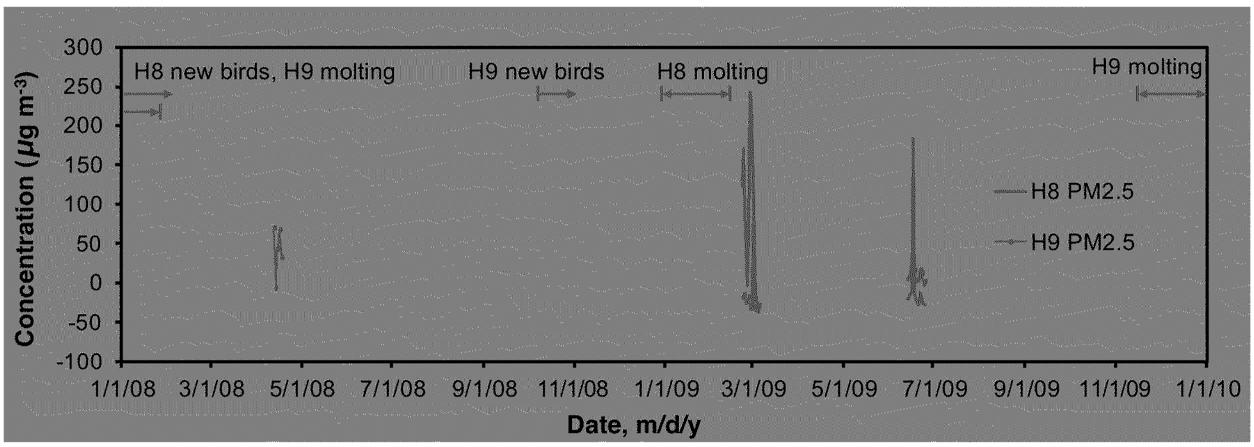

Figure 3.30. Daily mean $PM_{2.5}$ concentrations at IN2B.

Daily mean emission rates of $PM_{2.5}$ from both houses varied profoundly (Table 3-183.24). Negative emission rates were calculated due to $PM_{2.5}$ concentrations that were greater in ambient air than in house exhaust air. Seasonal emission variations cannot be clearly shown because of the limited number of measurements, compared with the PM_{10} measurement. Although H8 indicated higher emissions in winter than in summer 2009, H9 showed that the higher emission was in summer than in winter 2009 (Figure 3.31 and Figure 3.32).

Table 3-18. Mean (±SD) of house inlet and exhaust $PM_{2.5}$ emissions at IN2B.

Parameter	H8, g/d	H9, g/d	Shed, g/d	H8, g/d-AU	H9, g/d-AU	Shed, g/d-AU	H8, mg/d-hen	H9, mg/d-hen
2-yr valid days	25	31	30	25	31	30	25	31
Minimum DM	-1330	-199	3.2	-1.9	-0.3	0.0	-5.5	-0.8
Maximum DM	1388	688	320.5	2.1	0.9	0.2	5.6	2.8
1st yr ADM±SD		401±241	122±127		0.54±0.32	0.08±0.09		1.6±0.96
2nd yr ADM±SD	-85.1±676	44.2±192	29.8±30.1	-0.11±1	0.07±0.28	0.02±0.02	-0.38±2.75	0.18±0.78
2-yr ADM±SD	-85.1±676	113±247	48.3±73	-0.11±1	0.16±0.34	0.03±0.05	-0.38±2.75	0.46±0.99

The 2-yr ADM $PM_{2.5}$ emissions from H8 was negative (-85.1±676 g/d) and was invalid. In H9 and the shed, the total emissions were 113±247 and 48.3±73 g/d, respectively.

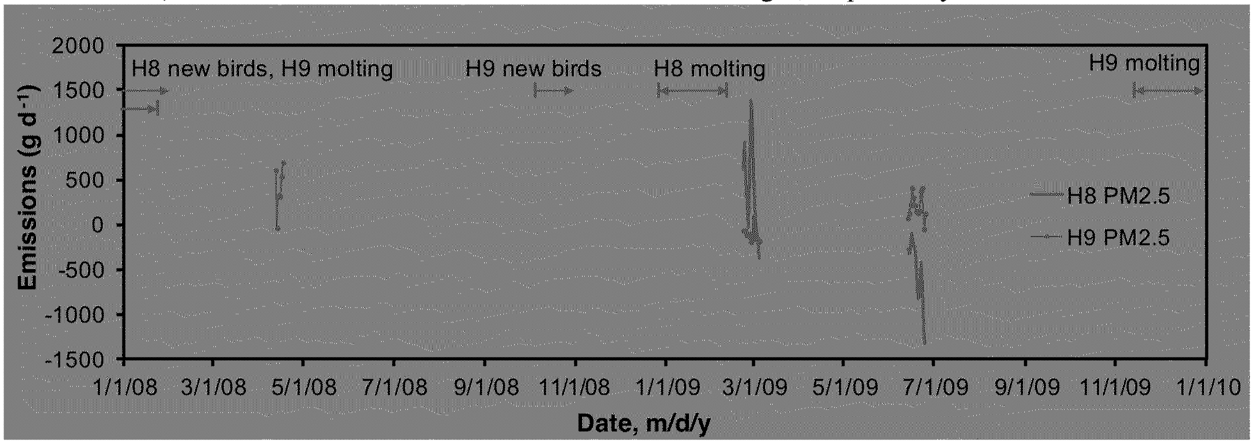

Figure 3.31. Daily mean $PM_{2.5}$ house emissions at IN2B.

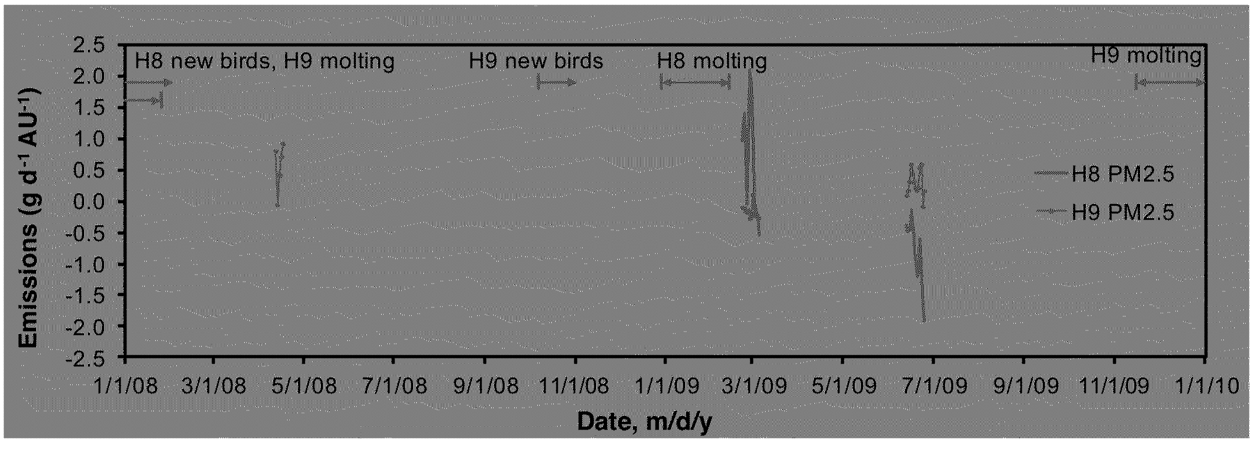

Figure 3.32. Daily mean LM-specific $PM_{2.5}$ emissions at IN2B.

3.3.9. VOC Concentration and Emissions

The 20 most prevalent VOCs detected in the canister samples accounted for 95% of the total quantified mass. The most prevalent compound was iso-propanol, which was 32% of the total mass (Table 3-29).

Table 3-19. Average concentration of 20 most prevalent VOCs at IN2B.

Compound	Conc., μg m^{-3}	% of total	Cumulative %
iso-Propanol	720	32.28	32.3
Pentane	242	10.86	43.1
Hexane	231	10.38	53.5
Methyl cyclopentane	132	5.93	59.4
Toluene	132	5.92	65.4
n-Propanol	130	5.85	71.2
2-Butanone	85.6	3.84	75.1
2,3-Butanedione	81.3	3.65	78.7
Acetaldehyde	68.9	3.09	81.8
Dimethyl sulfide	61.8	2.77	84.6
Hexanal	58.0	2.60	87.2
Dimethyl disulfide	38.9	1.74	88.9
Phenol	33.1	1.48	90.4
Acetic acid	24.6	1.10	91.5
Pentanal	17.5	0.79	92.3
2-Butanol	17.5	0.78	93.1
4-Methyl-phenol	14.0	0.63	93.7
1-Butanol	13.0	0.58	94.3
4-Ethyl-phenol	10.0	0.45	94.7
1-Pentanol	8.66	0.39	95.1
Total	2120	95.1	

Concentrations of total VOC in exhaust air ranged from 0. 62 to 4.37 mg m^{-3} in H8, and from 0.67 to 6.92 mg m^{-3} in H9. The mean total VOC concentrations were 2.05±1.32 in H8, 2.41±2.28 mg m^{-3} in H9, respectively (Table 3-30).

Total VOC emissions (mg s^{-1}) during each sampling period were determined by multiplying the mean building airflow rate (m^3 s^{-1}) by the total mass (mg m^{-3}) and converting to kg d^{-1}. The VOC emission rates of H8 and H9 ranged from 4.88 to 27.7 and 0.87 to 20.3 kg d^{-1}, respectively (Table 3-30). The mean VOC emission rates from H8 and H9 were 10.8±7.82 and 7.65±8.67 kg d^{-1} or 0.046±0.033 and 0.032±0.036 g d^{-1} hd^{-1}, respectively. These were actual measurements without any adjustments. These results are different than reported in the EPA report due to incorrect airflow rates and some incorrect concentrations used in the calculations. The correct results will be submitted to the EPA in a revised final report.

Table 3-30. Emissions of total VOC for each sampling day at IN2B.

Date	# canisters		Concentration, mg m^{-3}		Airflow, $m^3 s^{-1}$		Emission, kg d^{-1}	
	H8	H9	H8	H9	H8	H9	H8	H9
9/24/09	2	2	0.62	0.67	90.6	88.1	4.88	5.12
10/1/09	2	2	0.88	0.78	74.6	30.5	5.70	2.06
10/7/09	2	2	4.37	6.92	73.5	34.0	27.7	20.3
10/19/09	2	2	1.66	3.14	67.5	73.8	9.7	20.0
11/4/09	2	2	1.40	1.30	67.1	14.4	8.1	1.62
11/18/09	2	2	1.35	1.39	66.9	29.4	7.8	3.53
12/9/09	2	2	2.42	0.96	57.3	10.5	12.0	0.87
Mean	2	2	1.82	2.17	71.1	40.1	10.8	7.65

3.3.10. Pollutant Emissions per Dozen Eggs

Pollutant emissions per dozen eggs were calculated with a different methodology than hen-specific or LM-specific emission rates. The emissions per dozen eggs were calculated by dividing the 2-yr daily mean house emissions by the 2-yr daily mean egg production. This was because empty house days and molting periods greatly affect egg production rates. The IN2B emissions per day per dozen egg are presented in Table 3-313.27. Except for CO_2, which is not among the reportable pollutants, NH_3 showed the highest emissions per dozen eggs, followed by total VOC, PM_{10}, H_2S, and $PM_{2.5}$.

Table 3-31. Emissions per day per dozen egg production for six pollutants at IN2B.

Pollutant	House 8	House 9	Shed	Site average
CO_2, g/d-doz	1663	1784	3	1725
NH_3, g/d-doz	4.64	4.72	0.16	4.76
VOC, mg/d-doz	808	577	NA	692
PM_{10}, mg/d-doz	203	431	5	319
H_2S, mg/d-doz	32.1	33.3	1.2	33.3
$PM_{2.5}$, mg/d-doz	-5.59	8.03	1.65	2.04

3.4. Uncertainties in Airflow and Emission Rate

The quality of the emission rate data is an important issue for agricultural air quality research. Therefore, to estimate the quality of emission rate measurements, the uncertainties in the measured variables that are used in calculating emission rate must be determined. The total uncertainty of any measurement is a combination of systematic and random errors, which are quantified in this Section. The emission rate uncertainty arises from the measurement instrument's¬ uncertainty¬ and¬ variation¬ in¬ components¬ that¬ affect¬ determinatio as indoor and ambient environmental conditions, pollutant concentrations and airflow rate. Therefore, uncertainties in airflow, pollutant concentration, indoor air temperature and static pressure contribute to pollutant emission rate uncertainty.

The airflow uncertainty was calculated by using root square mean differences between fan airflow tests and the airflow model derived from the fan-law-adjusted BESS curves, number of fans operating simultaneously, and average airflow rate. Some of these components are given in

Table 3-323.28. Also, ventilation fan stages which controlled house airflow rates were considered in calculating airflow uncertainty. Both houses at IN2B site were ventilated with the same ventilation stages, with each stage controlling variable and single speed fans of 132-cm diameter.

Table 3-32. Fan airflow test standard deviations for houses in IN2B site.

Fan Diameter cm	Ref. spd (N_2)	House	Fans/House	Stages	Fan tests		Fan Operation	
					n	RMSD	Min	Max
132 (VS)		H8,H9	7	V			14	14
132		H8,H9	44	1-12			4	88

Airflow rate uncertainties in both houses ranged from 3.9 to 17.3%, with an average of the two houses of 7.5% (Figure 3.33). Moving from lower to higher stages decreased the standard error or uncertainty, as fan size in stages were the same and the number of operating fans (and therefore the total ventilation rate) increased. However, moving from stage V (variable fans) to stage 1 increased the standard error, as the single speed fans that begin operating with stage 1 had larger standard errors than did the variable speed fans on Stages V. For the higher stages (2-12), the uncertainty in airflow rate again deceased as the total number of operating fans increased.

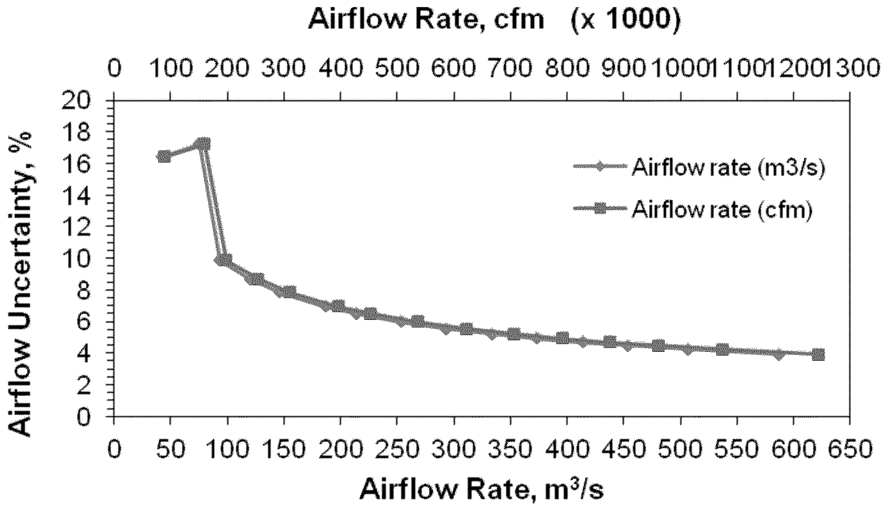

Figure 3.34 shows the dependence of emission rate uncertainty on house airflow.

The pattern of emission rate uncertainties is similar to the airflow rate uncertainty, as the total airflow rate accounts for most of the uncertainty in the calculation of emissions (Table 3-323.28). Uncertainties in the measurement of concentration are comparatively small. For H8 and H9, the emission uncertainties decreased with increased airflow rate (Table 3-333.29). The averages of emission uncertainties for the houses were 8.0% for NH_3, 7.6% for H_2S, 15.9% for PM_{10}, 14.7% for $PM_{2.5}$, and 16.5% for TSP.

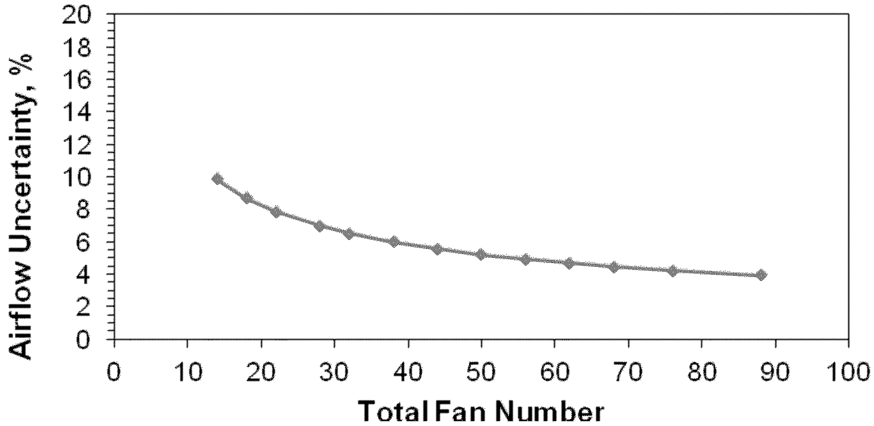

Figure 3.33. Variation of airflow uncertainty for IN2B site.

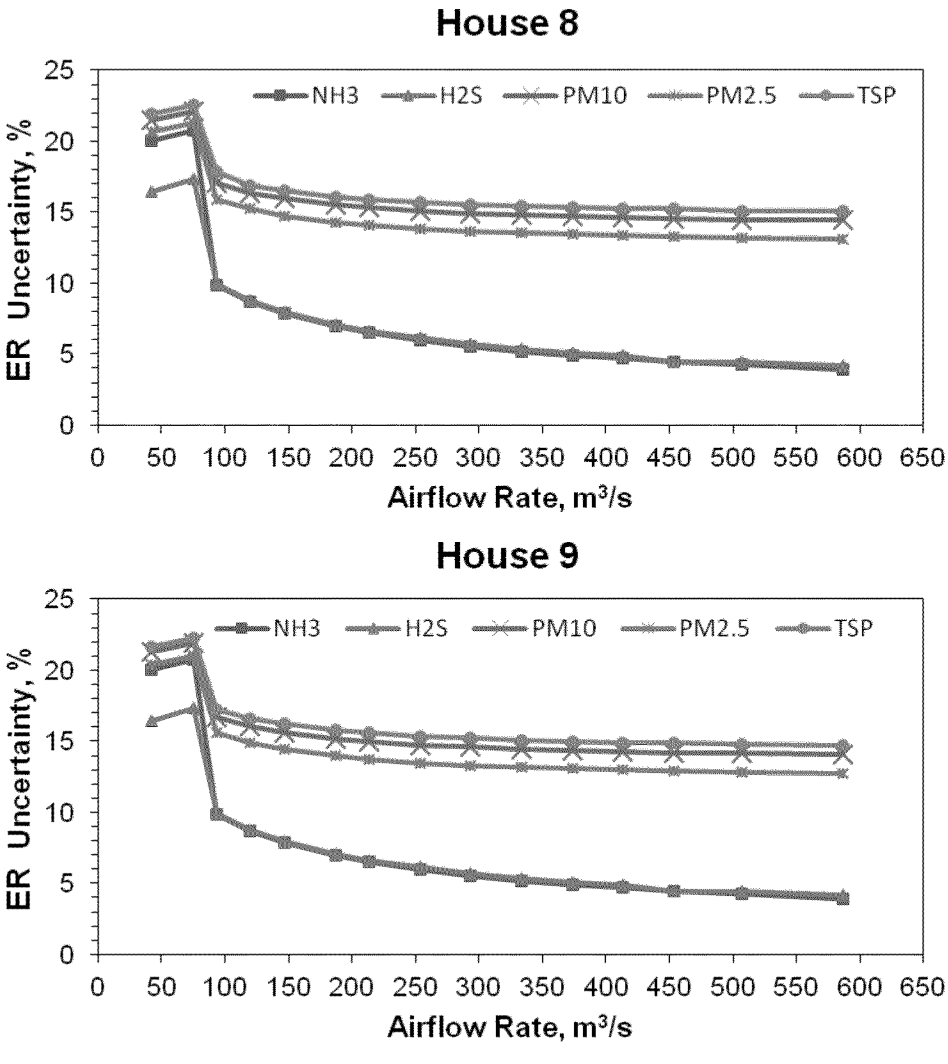

Figure 3.34. The variation of emission rate uncertainty with total airflow rate at IN2B.

Table 3-33. Averages and ranges of emission rate uncertainties.

Pollutant	Range, %		Average, %	
	H8	H9	H8	H9
NH_3	3.9 – 20.7	3.9 – 20.7	8.0	8.0
H_2S	4.1 – 17.3	4.1 – 17.3	7.6	7.6
PM_{10}	14.4– 22.1	14.1 – 21.9	16.1	15.8
$PM_{2.5}$	13.1– 21.3	12.7 – 21.1	14.9	14.6
TSP	15.0 – 22.6	14.7 – 22.3	16.7	16.4

4. DISCUSSION OF THE IN2H DATA

4.1. Introduction

The IN2H monitoring site was located on the same egg production facility as the IN2B site. Descriptions about the facilities are provided in Section 3.1.1. Houses 6 and 7 (built in 1997) at the facility were selected for monitoring. In these two high-rise houses, hens were raised in ten rows of A-frame cages in five tiers in the cage level or upper floor, and were molted according to industry standards. The lights at cage level were shut off for 8 h each night. Manure dropped off slanted boards behind the cages directly into the manure pit or first floor, where it was stored for up to one year or more. The characteristics of both houses are provided in Table 4-14.1.

Table 4-1. Characteristics of houses at the IN2H site.

Descriptive Parameters	Each house
Year of construction	1997
House capacity and type	250,000 hens, high-rise
Hen space	0.04 m^2/hen
House orientation	E-W
Genetics of hens and average weight	W36, 1.5 kg
Hen occupation, d	700
Molt of the hens	Yes
Number of tiers and rows of cages	5 tiers 10 rows
Type of cages	Big Dutchman 520 N
House length x width, m	198 x 30.5
Ridge height, m	8.5
Sidewall and manure pit height, m	5 and 2.4
House spacing, m	17
Manure accumulation in pit, d	365
Manure collection method	Skid loader
Ventilation type	Mechanical
Number of pit circulation fans	50
Inlet number and type	3 V-shaped baffles
Inlet control basis/adjustment method	Temperature/cable
Control system vendor/manufacturer	Fancom
Walls with fans	North and south side walls
Number of single-speed and variable-speed fans	100 and 10
Fan manufacturer and fan diameter, m	Aerotech 1.2 m
Fan spacing	Varies
# ventilation stages	Variable-speed fan + 12 stages
# temperature sensors	12

Figure 4.1 is an east-end view of the houses and the OFIS, which was parked between H6 and H7, but close to house 7 to avoid the steep slope of a drainage ditch. Approximate locations of the sensors, air sample probes, and TEOMs are indicated on the floor plan and eastern side view drawings (Figure 4.2).

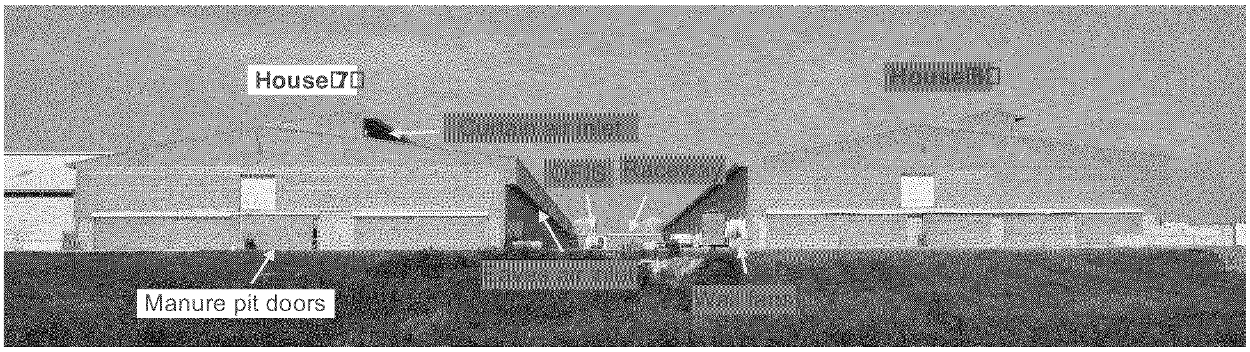

Figure 4.1. East side view of houses 6 and 7 at IN2H.

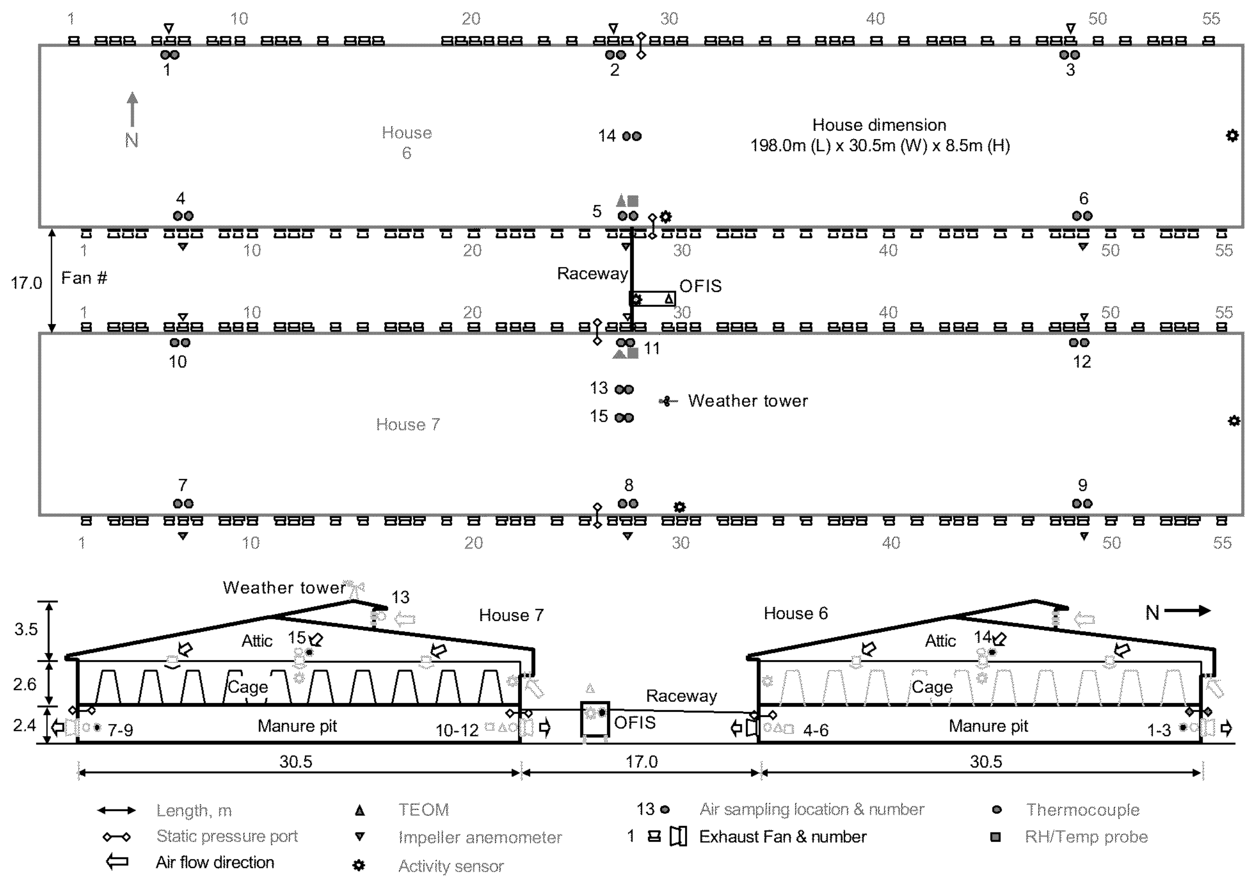

Figure 4.2. Floor plan and eastern side-view of H6 and H7 with sensor locations.

4.2. Quality Control and Quality Assurance of Carbon Dioxide Measurement

While the NAEMS EPA report presented NH_3 and H_2S measurements, it did not include carbon dioxide (CO_2). The quality control and quality assurance procedures related to CO_2 measurement are presented in this section.

Carbon dioxide concentration was measured using a photoacoustic infrared INNOVA 1412 (LumaSense Technologies A/S, Ballerup, Denmark). Multipoint calibrations (MPCs) using zero air and span CO_2 in nitrogen (Praxair, Indianapolis, IN) were conducted five (5) times to assess linearity (Table 4-24.2). Data from an example MPC are presented in Figure 4.3.

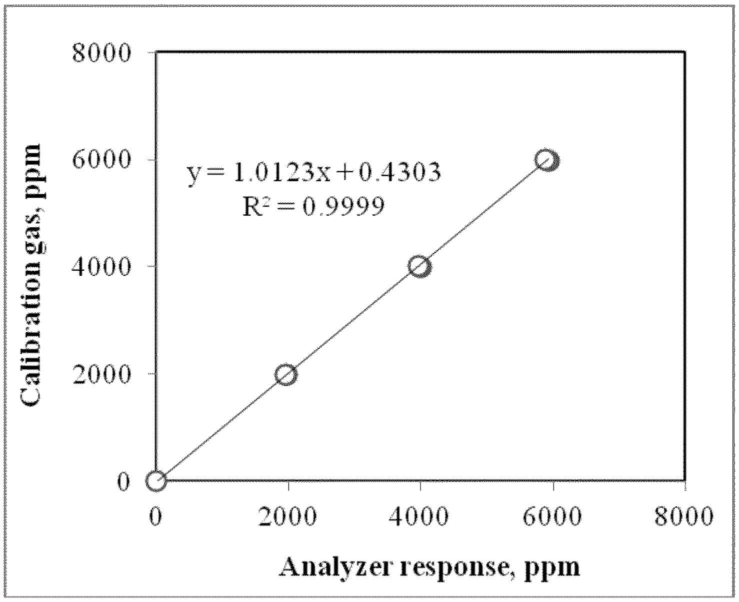

Figure 4.3. An example of multi-point calibration of CO_2 responses on 5/23/07.

Table 4-2. Multipoint CO_2 measurement calibration and results at IN2H.

Date	# of points	Span concentration, ppm		R^2
		Minimum	Maximum	
05/23/07	4	2000	6000	0.999
11/09/07	4	1500	4000	0.999
03/07/08	3	4000	9000	0.999
10/15/08	3	4000	8000	0.999
01/29/09	4	2500	9000	0.999

Zero and span (4000 ppm CO_2) checks were conducted weekly (Figure 4.4). All span check responses were within the ±10% level. The response exceeded 50 ppm during six zero checks. Instrument readouts of CO_2 were corrected based on the zero-span check results during data processing.

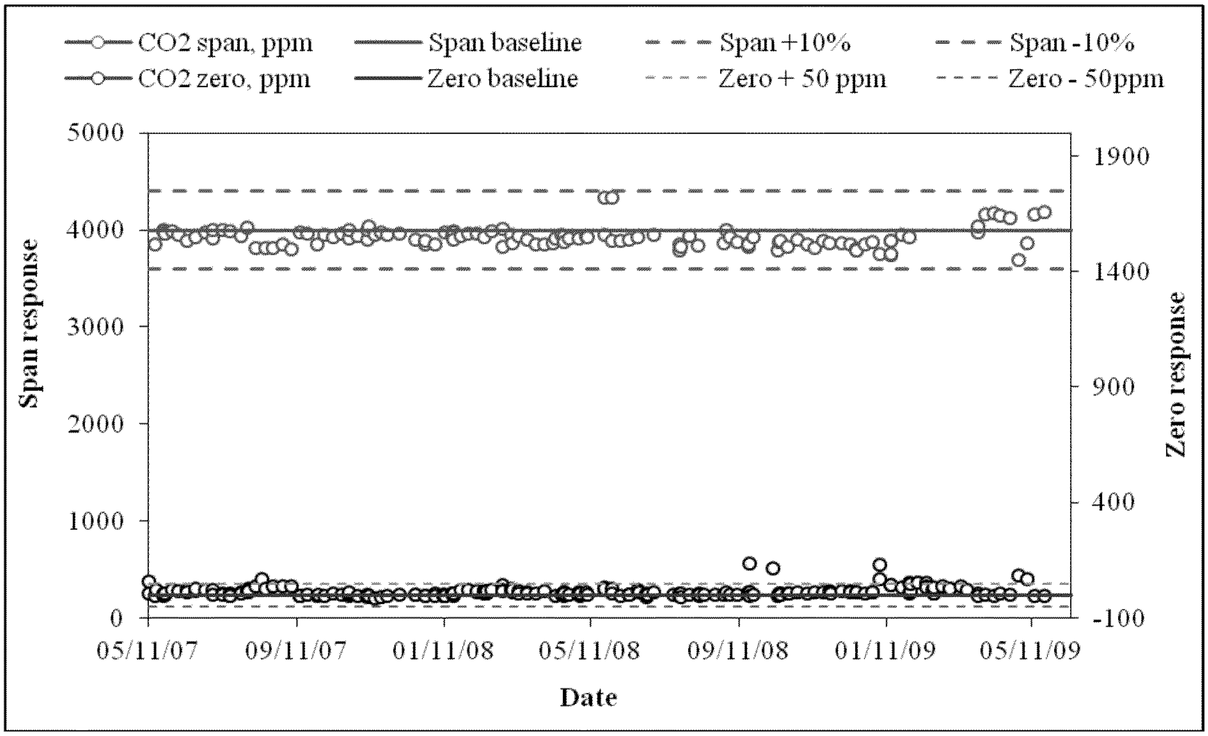

Figure 4.4. Results of weekly zero and span checks of CO_2 measurement at IN2H.

4.3. Results

4.3.1. Animal Characteristics

Hen characteristics, including inventory, average weight and live mass density are presented in Table 4.3. The hen inventory and average weight were derived from weekly data sheets provided by the producer. New flocks were placed in houses 7 and 6 in July 2007 and April 2009, respectively (Figure 4.5).

The average inventories of H6 and H7 were 218,000±22,400 and 218,000±21,400, respectively. The average hen weight ranged from 1.23 to 1.60 kg in house 6 (H6) and 1.21 to 1.60 kg in house 7 (H7). Hen weights decreased during molt of H6 and H7 in May and September, 2008, respectively. Hen weights of new flocks were initially low (Figure 4.6). The daily mean egg production rates were 155,000±61,900 in H6 and 153,100±61,400 in H7. The flock sizes and daily egg production rates were not statistically different ($P>0.05$) between houses. However, the differences in average hen weights were statistically significant ($P<0.05$).

Table 4-3. Annual and 2-yr ADM of flock parameters at site IN2H.

Parameter	House 6 means (±SD)			House 7 means (±SD)		
	Hens,┐ 1000	**Wt, kg**	**Eggs, k**	**Hens,┐ 1000**	**Wt, kg**	**Eggs, k**
2-yr valid days	731	723	731	731	726	731
Minimum DM	0	1.23	0.00	0	1.21	0.00
Maximum DM	232.2	1.60	219.87	232.4	1.60	221.6
1st yr ADM±SD	228±3.8	1.43±0.06	173±63.6	223±29.2	1.42±0.07	168.4±65.7
2nd yr ADM±SD	208±28.3	1.45±0.06	137±54.6	214±4.9	1.49±0.08	137.9±52.4
2-yr ADM±SD	218±22.4	1.44±0.06	155±61.9	218±21.4	1.46±0.08	153.1±61.4

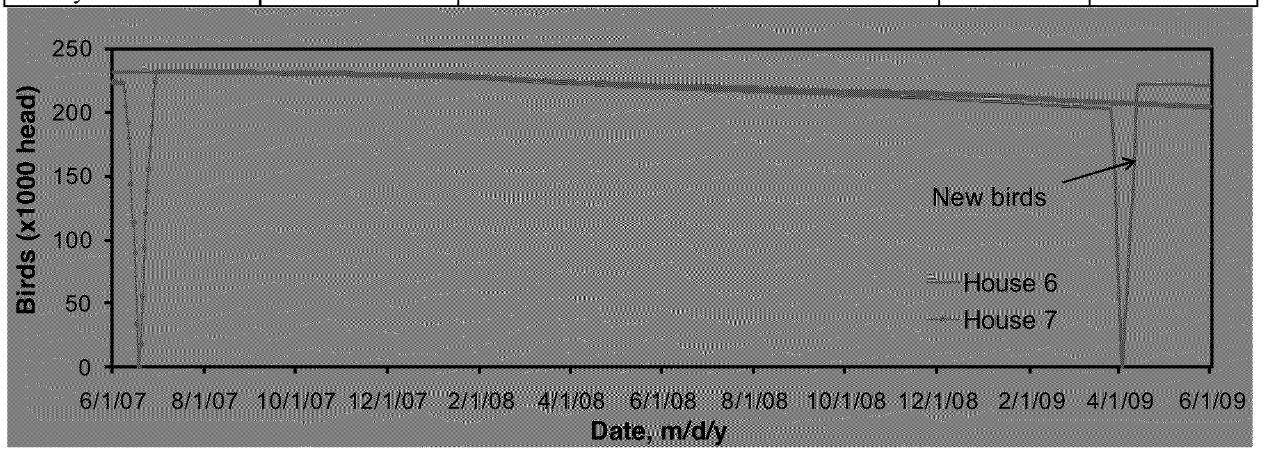

Figure 4.5. Hen inventories in two houses at IN2H.

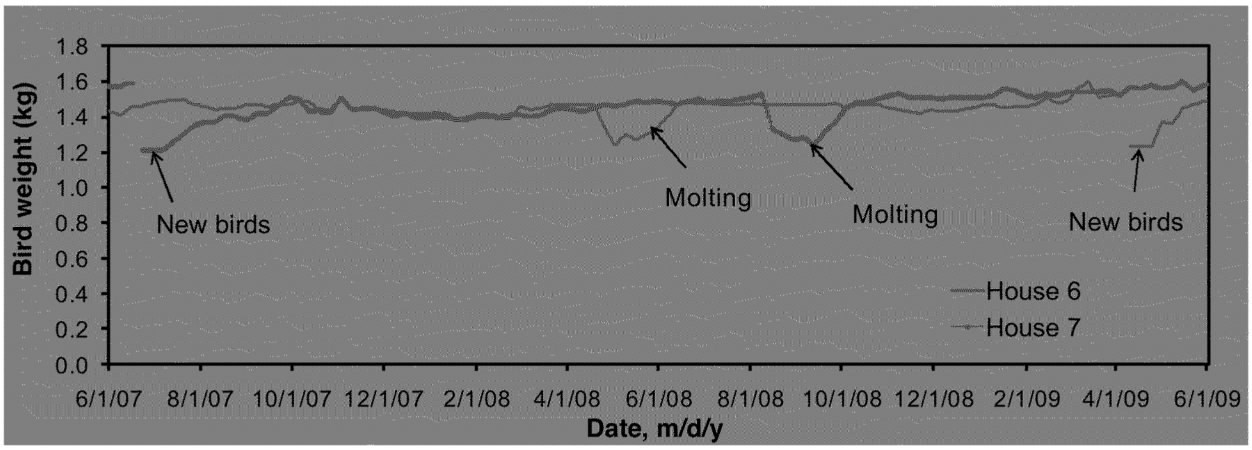

Figure 4.6. Average hen weight at IN2H.

4.3.2. Environmental Conditions and Airflow

4.3.2.1. Temperature

The daily mean ambient temperatures ranged from -18.4 to 29.4 °C (Table 4-44.4 and Figure 4.7). The ADM ambient temperature was 12.4±11.3°C (mean±SD). The ADM pit-level temperatures were 22.3±3.7 and 22.5±3.7 °C for H6 and H7, respectively. They were very close and did not show statistical difference between the two houses ($P>0.05$). At cage-levels (Table 4-44.4 and Figure 4.8), the ADM tempertures were 27.5±2.5 and 25.8±2.3°C for H6 and H7, respectively, and were statistically different ($P<0.05$). Temperatures in H6 were greater than H7 during both years.

Table 4-4. Annual and two-year means of ambient and indoor temperature at IN2H.

Variable	Ambient T, °C	H6 pit T, °C	H7 pit T, °C	H6 cage T, °C	H7 cage T, °C
2-yr valid days	700	700	700	700	699
Minimum DM	-18.4	9.8	8.5	11.9	19.5
Maximum DM	29.8	30.0	31.0	31.9	31.3
1st yr ADM±SD	12.5±11.1	22.3±3.5	22.7±3.3	27.1±1.7	26.0±2.0
2nd yr ADM±SD	12.2±11.4	22.3±3.9	22.4±4.1	27.9±3.1	25.6±2.6
2-yr ADM±SD	12.4±11.3	22.3±3.7	22.5±3.7	27.5±2.5	25.8±2.3

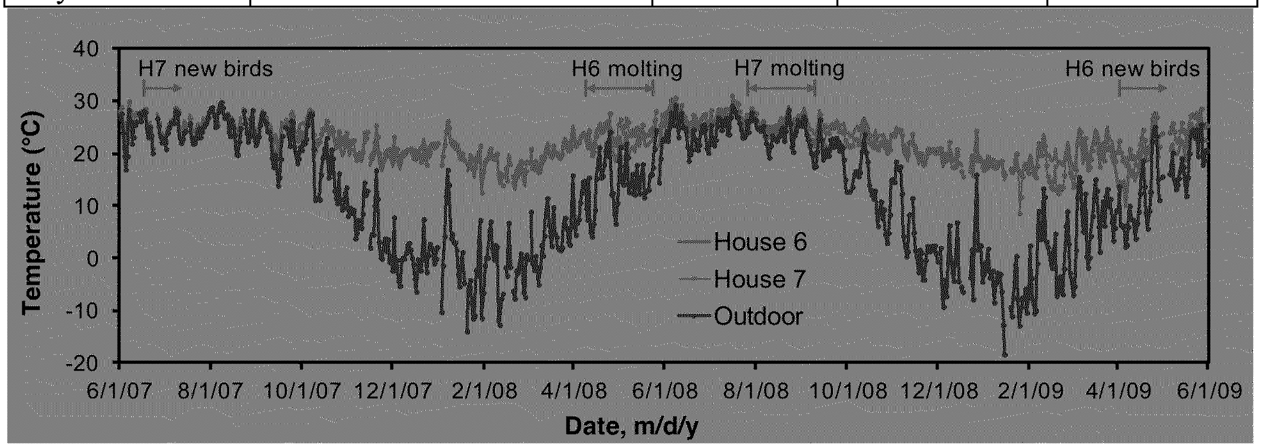

Figure 4.7. Daily mean ambient and manure pit temperature at IN2H.

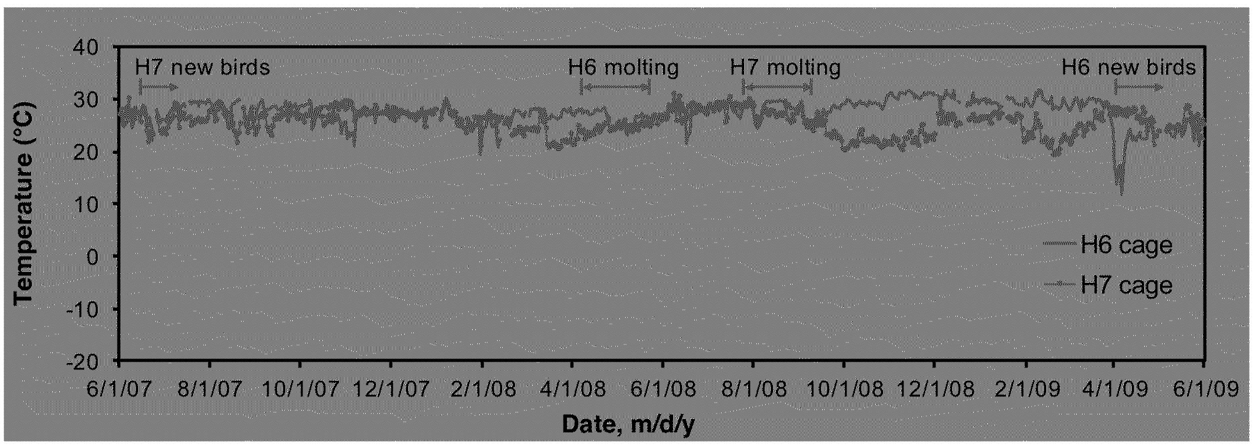

Figure 4.8. Daily mean indoor (cage) temperature at IN2H.

4.3.2.2. Relative Humidity

The daily mean ambient relative humidity (RH) ranged from 34.6 to 97.8% (Table 4-54.5 and Figure 4.10). Ambient RH fluctuated more than indoor RH in both houses (Figure 4.9 and Figure 4.10). The ADM ambient RH was 68.2±13.3% while the ADM pit-level RHs were 51.8±8.5 and 52.8±9.8% for H6 and H7, respectively. The cage-level ADM RHs were 48.7±5.5 and 51.6±6.1% for H6 and H7, respectively. In each house, the pit and cage RH were statistically different ($P<0.05$). No statistical difference was observed between the pits of the two houses ($P>0.05$). However, the cage RH between houses were different ($P<0.05$).

Table 4-5. Annual and two-year means of ambient and indoor RH at IN2H.

Parameter	Ambient, %	H6 pit, %	H6 cage, %	H7 pit, %	H7 cage, %
2-yr valid days	669	701	701	651	700
Minimum DM	34.6	27.9	31.8	30.4	34.5
Maximum DM	97.8	78.0	65.5	79.6	66.9
1st yr ADM±SD	69.0±13.4	52.3±8.4	47.9±5.4	54.7±10.1	50.6±5.9
2nd yr ADM±SD	67.5±13.2	51.4±8.5	49.6±5.5	50.5±8.7	52.6±6.2
2-yr ADM±SD	68.2±13.3	51.8±8.5	48.7±5.5	52.8±9.8	51.6±6.1

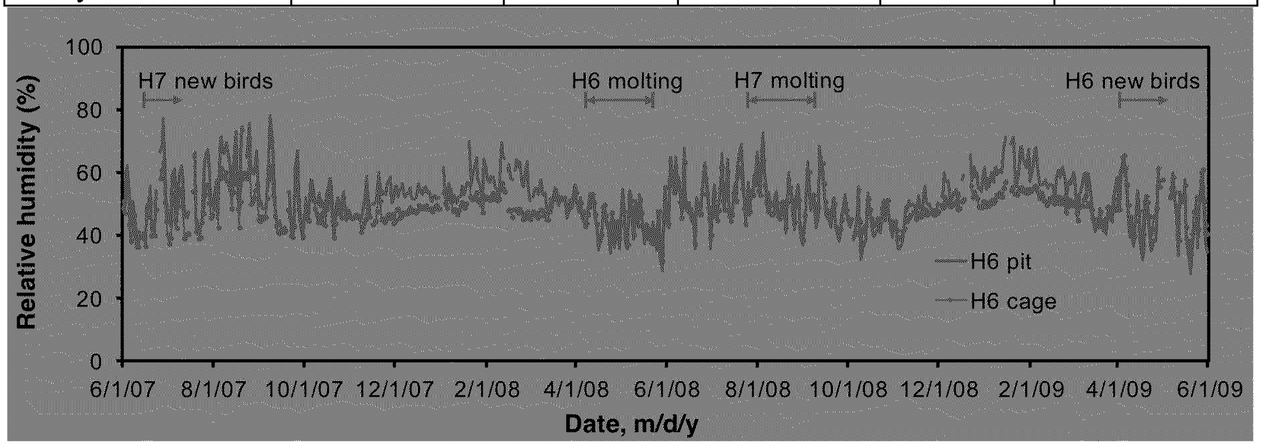

Figure 4.9. Daily mean relative humidity in house 6 pit and cage at IN2H.

Due to a technical issues related to the sensor, some H7 pit data were invalidated from December 2008 to January 2009, which reduced the number of valid days to 651 d compared with 700 d for other indoor RH data.

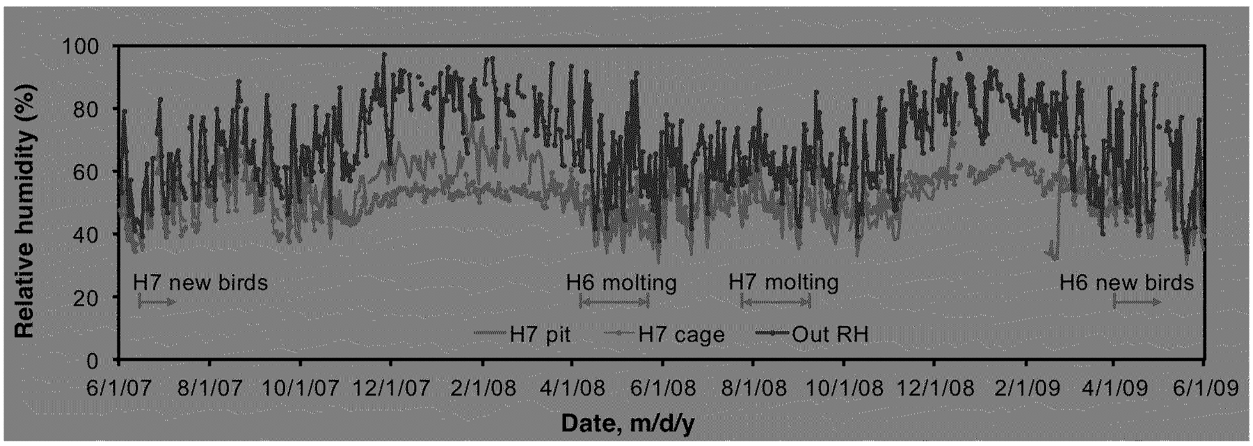

Figure 4.10. Daily mean RH in ambient air and in house 7 pit and cage at IN2H.

4.3.2.3. Static Pressure

Static pressure measurements in H6 and H7 produced 700 d of valid data (Table 4-64.6), and ranges of static pressures were from -39.1 to -0.6 Pa and from -53.8 to -0.7 Pa, respectively. Low pressures of <-50 Pa in H7 occurred on only 2 d (Figure 4.11). The ADM pressures were -17.6±6.7 Pa for H6 and -19.1±7.3 Pa for H7 and were statistically different (P<0.05). Daily mean static pressures (Figure 4.11) did not exhibit seasonal patterns that could have otherwise been related to ambient temperatures or other environmental variables.

Table 4-6. Annual and two-year means of differential pressure and airflow rate.

Parameter	House dP, Pa		Airflow, m^3/s		Airflow, m^3/h-hen	
	H6	H7	H6	H7	H6	H7
2-yr valid days	700	700	652	640	651	553
Minimum DM	-39.1	-53.8	13.6	32.7	0.56	0.52
Maximum DM	-0.6	-0.7	694.2	724.0	11.24	11.23
1st yr ADM±SD	-17.6±8.0	-17.3±7.9	192±185	225±214	3.02±2.87	3.4±3.31
2nd yr ADM±SD	-17.7±5.1	-20.9±6.1	178±158	178±152	3.02±2.58	2.76±2.33
2-yr ADM±SD	-17.6±6.7	-19.1±7.3	185±172	202±187	3.02±2.73	3.11±2.93

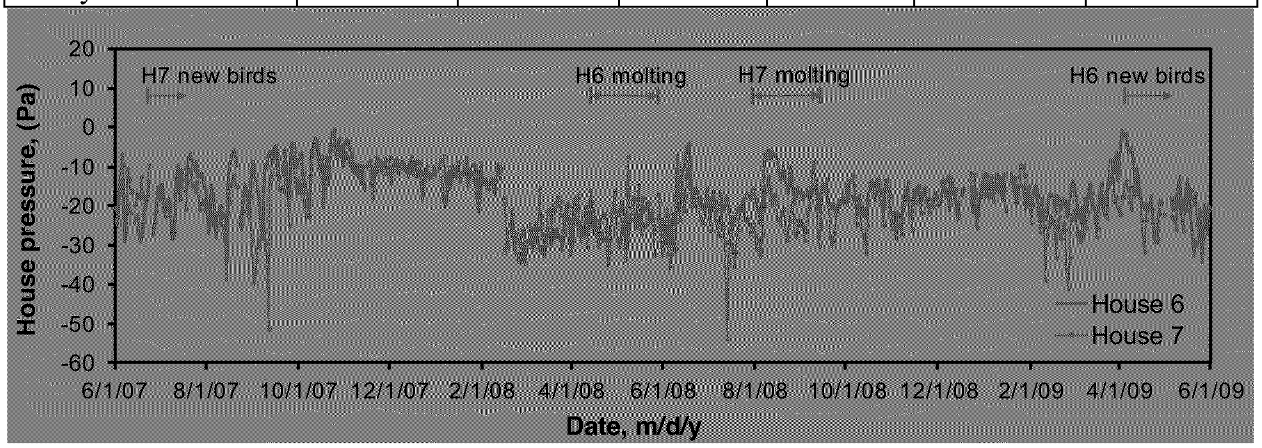

Figure 4.11. Daily mean house static pressures at IN2H.

4.3.2.4. Ventilation Rate

Daily mean house ventilation rates in H6 and H7 ranged from 13.6 to 694.2 m^3/s, and from 32.7 to 724.0 m^3/s, and the ADM ventilation rates were 185±172 and 202±187 m^3/s, or 3.02±2.73 and 3.11±2.93 m^3/h-hen, respectively (Table 4-64.6). No statistical differences between houses were observed for house- and hen-specific ventilation rates ($P>0.05$). The ventilation rates were closely and inversely correlated with ambient temperature and exhibited distinct seasonal variations (Figure 4.12). Because house inventories were nearly constant, the hen-specific ventilation rates also followed the same patterns (Figure 4.13). The maximum ventilation rates occurred at the beginning of August 2007, when the hen-specific rates were greater than 11 m^3/h-hen (Figure 4.13). The minimum daily hen-specific ventilation rates occurred from November to April.

4.3.3. Ammonia Concentration and Emissions

The characteristics of daily mean inlet and pit exhaust NH_3 concentrations are listed in Table 4-74.7. The ADM NH_3 concentration of ambient air (measured at the roof top of H7) was 1.2±1.3 ppm, while those in the inlets (attics) were 1.7±2.4 ppm in H6 and 2.2±3.0 ppm in H7 (Figure 4.14). Higher inlet concentrations occurred during winter when the ventilation rates were low and the exhaust NH_3 concentrations were high. Attic concentrations were higher than ambient air. The two attic concentrations did not exhibit statistical differences ($P<0.05$).

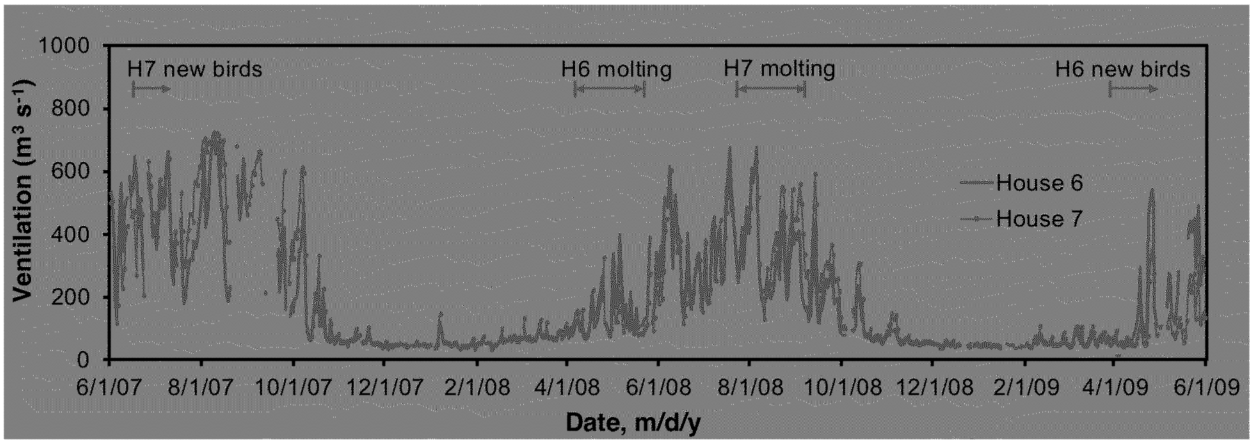

Figure 4.12. Daily mean house ventilation rate at IN2H.

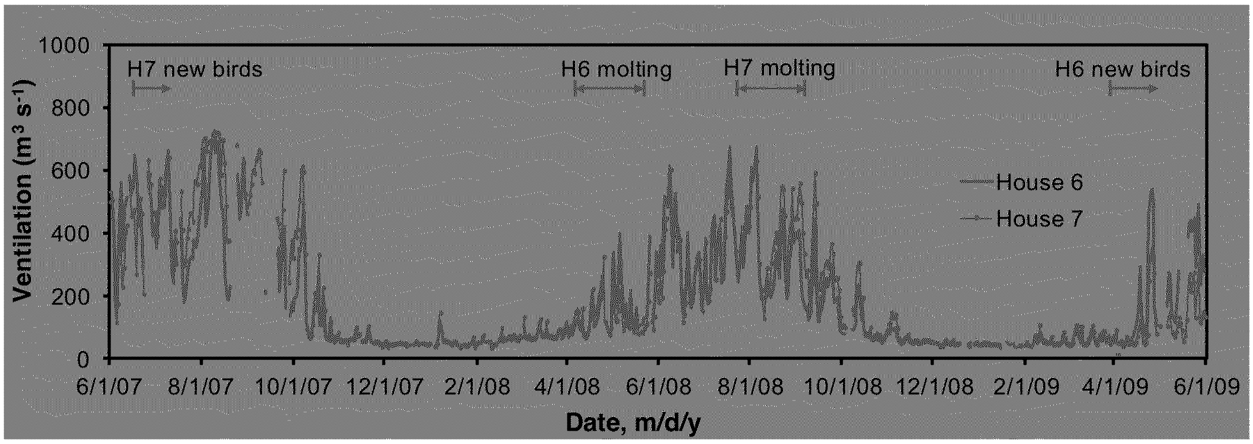

Figure 4.13. Daily mean hen-specific ventilation rate at IN2H.

Table 4-7. Summary of ammonia concentrations (ppm) at IN2H.

Parameter	Ambient	H6 Inlet	H7 Inlet	H6 Exhaust	H7 Exhaust
2-yr valid days	613	615	637	625	631
Minimum DM	-1.59	-2.09	-2.16	0.5	1.2
Maximum DM	6.38	9.44	13.42	175.7	182.0
1st yr ADM±SD	1.6±1.3	2±2.3	2.9±3.3	49.9±39.6	55.5±44.2
2nd yr ADM±SD	0.7±1.2	1.3±2.5	1.5±2.5	47.7±38.3	48±36.2
2-yr ADM±SD	1.2±1.3	1.7±2.4	2.2±3.0	48.9±39	51.9±40.7

The ADM NH_3 exhaust concentrations were 48.9±39.0 and 51.9±40.7 ppm in H6 and H7, respectively. Seasonal exhaust concentration variations (Figure 4.15) were closely related to variations in ambient temperatures and house ventilation rates. The exhaust NH_3 concentrations were greatly reduced at higher ambient temperatures and ventilation rates. However, NH_3 concentrations also depended on the NH_3 production in the houses, even though there were some seasonal fluctuations in the inlet NH_3 levels. The exceptionally low NH_3 concentrations during the molting period occurred because the hens were provided with limited feed, resulting in greatly reduced manure production and NH_3 release.

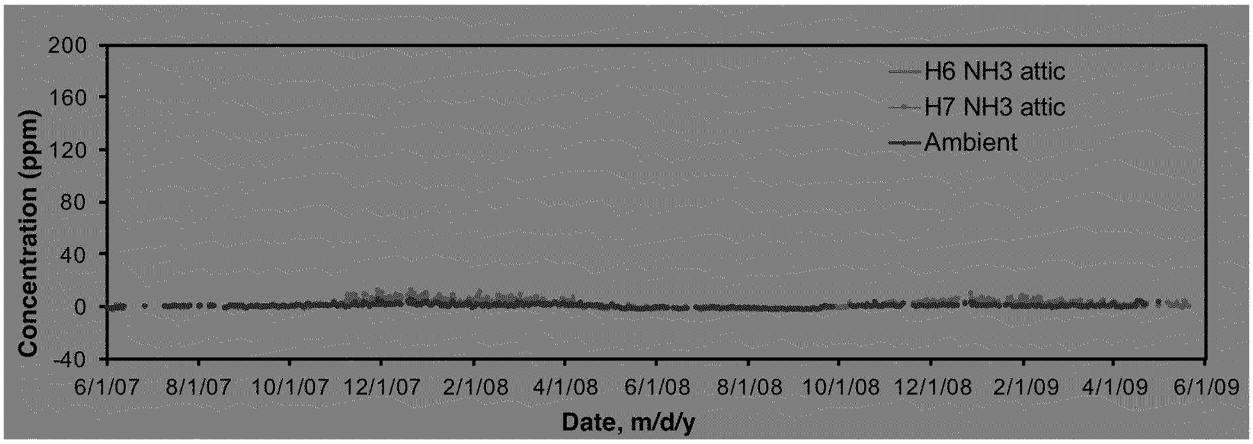

Figure 4.14. Daily mean ammonia concentrations at house inlets and ambient air at IN2H.

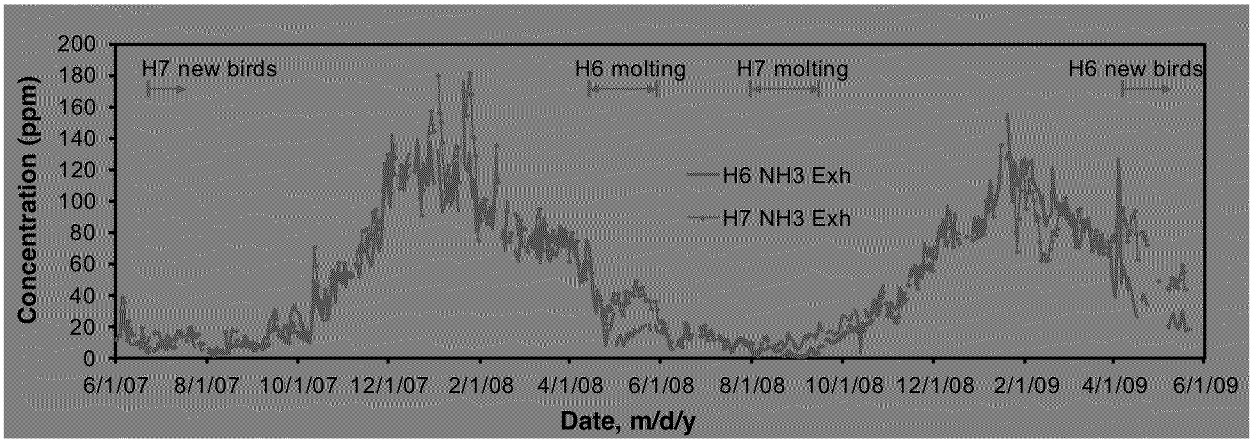

Figure 4.15. Daily mean ammonia concentrations at house exhausts at IN2H.

Table 4-84.8 lists characteristics NH_3 emissions from both houses in different units. The valid days for house NH_3 emissions were 525 d for H6 and 512 d for H7. Due to the empty houses with no hens kept and eggs produced, and molting periods with no eggs produced, the valid days for animal-specific (LM- and hen-specific emission) were fewer.

The 2-yr ADM house NH_3 emissions were 223±86 and 249±97 kg/d for H6 and H7, respectively. Emission from H7 was statistically higher than that from H6 ($P<0.05$). However, the two emission rates do not have significant statistical difference ($P>0.05$).

The 2-yr ADM NH_3 emissions per animal unit were 355±135 g/d-AU from H6 and 386±149 g/d-AU from H7. House 6 emissions were statistically higher than H7. Hen-specific emissions ranged from 0.2 to 2.7 g/d-hen and averaged 1.03±0.4 g/d-hen for H6. They ranged from 0.3 to 4.0 g/d-hen and averaged 1.13±0.43 g/d-hen for H7. Like the LM-specific emissions, the hen-specific emissions was also statistically different between the two houses ($P<0.05$).

Table 4-8. Summary of ammonia emissions at IN2H.

Parameter	House, kg/d		Per AU, g/d-AU		Per hen, g/d-hen	
	H6	H7	H6	H7	H6	H7
2-yr valid days	525	512	511	512	511	512
Minimum DM	37	57	79	102	0.2	0.3
Maximum DM	613	916	964	1410	2.7	4.0
1st yr ADM±SD	248±83	297±90	384±126	456±142	1.1±0.4	1.3±0.4
2nd yr ADM±SD	200±83	203±81	328±137	317±121	1.0±0.4	1.0±0.4
2-yr ADM±SD	223±86	249±97	355±135	386±149	1.03±0.4	1.13±0.43

Variations of daily mean NH_3 emissions are displayed in Figure 4.16 for house emissions, Figure 4.17 for LM-specific emission, and Figure 4.18 for hen-specific emission. Because of relatively constant hen numbers in the houses, the emission patterns are similar among the three different emission units. Winter emissions were higher than summer emissions for both years. The main reasons were believed to be related to drier manure in summer. Emissions per dozen eggs are not plotted because of unreasonably high emissions during some molting days when very small quantities of eggs were produced.

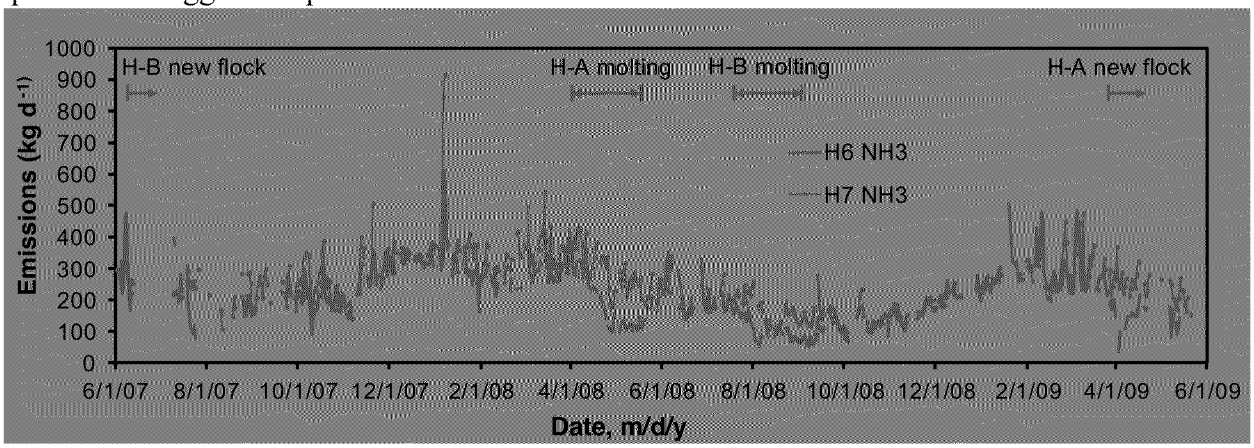

Figure 4.16. Daily mean ammonia house emission at IN2H.

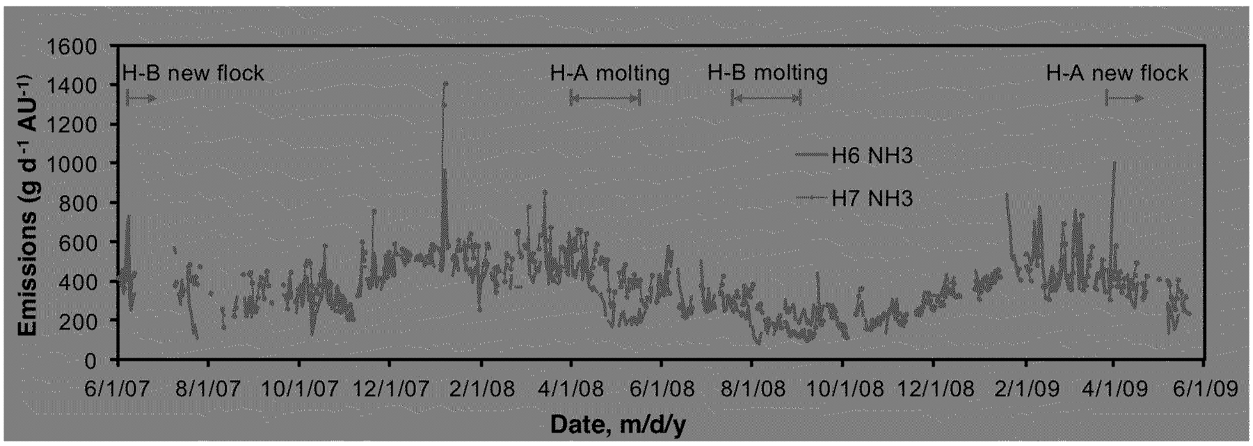

Figure 4.17. Daily mean LM-specific ammonia emission at IN2H.

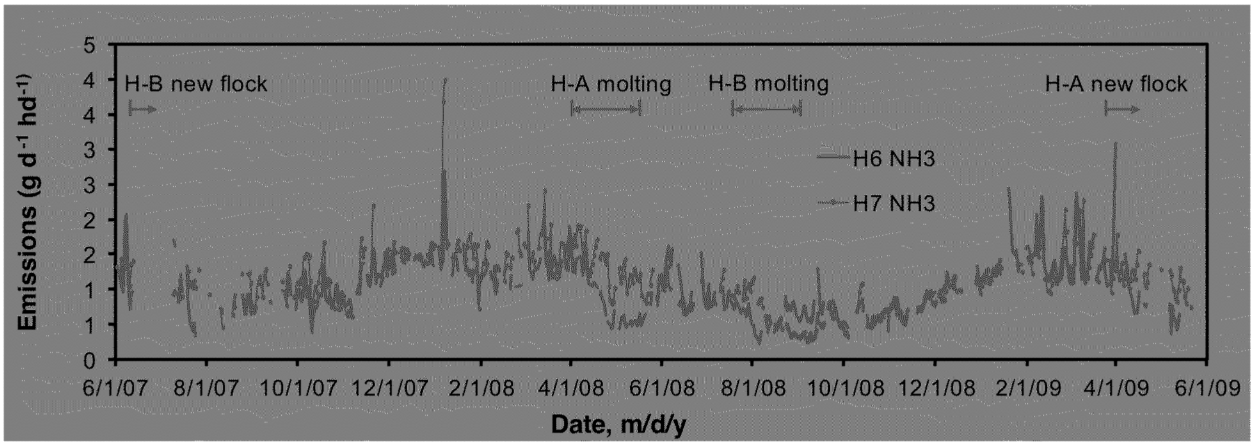

Figure 4.18. Daily mean hen-specific ammonia emission at IN2H.

Single-factor correlation analyses were conducted on the daily mean hen-specific NH_3 emission rates, with the results shown in Table 4.9. High-rise houses, due to drying out of manure with increased airflow, have the unique characteristic of lower NH_3 emissions in warm weather and higher emissions in cold weather when RH is highest and inlet temperature, and ventilation rate are the lowest. This explains the strong positive correlations with exhaust RH and strong negative correlations with inlet temperature, ventilation rate, and exhaust temperature. Direct positive influences were hen activity, LMD, and egg production.

Table 4.9. Parameters influencing area-specific ammonia emissions.

Parameter	Averaging Interval	R
Exhaust RH	Daily	0.336
Hen activity	Hourly	0.312
LMD	Hourly	0.239
Wind speed	Hourly	0.179
Eggs	Daily	0.118
Exhaust RH	Hourly	0.103
LMD	Daily	0.034
Solar	Hourly	0.020
Time of day	Hourly	-0.008*
Atmospheric pressure	Hourly	-0.090
Exhaust temp	Hourly	-0.099
Hen age	Hourly	-0.111
Hen age	Daily	-0.119
Ventilation	Hourly	-0.120
Static pressure	Hourly	-0.143
Exhaust temp	Daily	-0.192
Ventilation	Daily	-0.204
Inlet temp	Hourly	-0.242
Inlet temp	Daily	-0.288

Note: n=25162-26662 and 883-912 for hourly and daily means, respectively.

Multiple linear regression showed that ventilation rate, hen age, and LMD were the most significant factors for both hourly and daily mean emissions (Table 4.10). The house effect was significant for hourly mean estimations only. Manure age was not included in either analysis. Exhaust temperature only appeared as an interaction factor for daily means at the third level, however, its effect was most likely exhibited in the exhaust RH term which was at the top level in the interaction term with LMD.

Table 4.10. Correlations between area-specific NH_3 emission and various factors (*p>0.05).

Hourly Means of NH_3 Emissions		Daily Means of NH_3 Emissions	
Parameter	**R^2**	**Parameter**	**R^2**
Ventilation * Hen Age	0.448	LMD * Exhaust RH	0.114
LMD	0.512	Hen Age * Ventilation	0.172
Hen Age	0.574	Exhaust Temp * Exhaust RH	0.194
Time of Day * Hen Age	0.583	Inlet Temp * Exhaust RH	0.201
House	0.611	Eggs * Hen Age	0.241
Atmospheric Pressure * LMD	0.618	Exhaust RH * Ventilation	0.251
Atmospheric Pressure	0.623	LMD * Hen Age	0.270
Atmospheric Pressure * Hen Age	0.631	Hen Age * Exhaust Temp	0.294
Static Pressure * LMD	0.668	Hen Age * Inlet Temp	0.310
Static Pressure	0.675	Inlet Temp * Ventilation	0.338
Atmospheric Pressure * Static Pressure	0.695	Exhaust Temp * Ventilation	0.390
Ventilation * Static Pressure	0.708	Eggs * Exhaust RH	0.390
Exhaust Temp * Static Pressure	0.724	Exhaust RH	0.403
Static Pressure * Hen Age	0.732	Inlet Temp * Exhaust Temp	0.421
Ventilation	0.736	LMD * Ventilation	0.432
Time of Day * Static Pressure	0.757	LMD * Exhaust Temp	0.439
Time of Day * LMD	0.772	Inlet Temp	0.444
Time of Day * Exhaust Temp	0.772	Eggs * Ventilation	0.449
Time of Day * Ventilation	0.774		
Time of Day	0.776		
Ventilation * Atmospheric Pressure	0.777		
Exhaust Temp	0.778		
Exhaust Temp * Atmospheric Pressure	0.779		
Time of Day * Atmospheric Pressure	0.780		
Exhaust Temp * Hen Age	0.781		

The predictions using LMD and exhaust temperature resulted in very low R^2 values (Equations 4.1 and 4.2).

Hourly: $E = -42.30 - 0.581\,D + 1.790\,T$, $R^2 = 0.08$ (4.1)

Daily: $E = 19.72 + 0.176\,D - 0.921\,T$, $R^2 = 0.05$ (4.2)

4.3.4. Hydrogen Sulfide Concentration and Emissions

The characteristics of daily mean inlet and house exhaust H_2S concentrations are listed in Table 4-94.10. The valid days for H_2S concentrations measured at different locations ranged from 374 to 385 d. The low number of valid days, compared with IN2B site, was due to higher maintenance and repair requirements of the older version H_2S analyzer used at the IN2H site.

The 2-yr ADM H_2S concentration at the ambient background (H7 rooftop) was 24.9±19 ppb. Those at the houses inlets (attics) were 8.3±9.7 and 9±10.2 ppb for H6 and H7, respectively. Concentrations in the two house inlets did not make statistical difference (P>0.05). It is unclear why the concentration at the ambient background was higher than the house air inlets. The 2-yr ADM H_2S concentrations at the pit exhausts were 26.4±17.6 ppb in H6, and 24.9±19 ppb in H7. The H_2S concentration differences between houses were statistically insignificant (P>0.05).

Table 4-9. Summary of hydrogen sulfide concentrations (in ppb) at IN2H.

Parameter	Ambient	H6 Inlet	H7 Inlet	H6 Exhaust	H7 Exhaust
2-yr valid days	378	374	374	385	378
Minimum DM	2.0	-2.7	-3.1	3.2	2.0
Maximum DM	87.2	56.8	59.7	82.4	87.2
1st yr ADM±SD	38.2±18.1	14.7±7.4	15.8±7.8	36.3±17.9	38.2±18.1
2nd yr ADM±SD	11.9±7.1	2.7±7.8	3.3±8.4	16.6±10.3	11.9±7.1
2-yr ADM±SD	24.9±19	8.3±9.7	9±10.2	26.4±17.6	24.9±19

The 2-yr mean H_2S concentrations at this site were lower than in the IN2B houses (40.0±21.1 ppb in H8 and 41.2±31.5 in H9). Similarly, the maximum daily mean H_2S concentrations were also lower at this site than at IN2B. The daily mean H_2S concentrations (Figure 4.19 and Figure 4.20) exhibited seasonal variations, and also showed an inverse relationship to house ventilation rates. The effects of temperature and ventilation on H_2S concentrations were not as profound as on NH_3 concentrations.

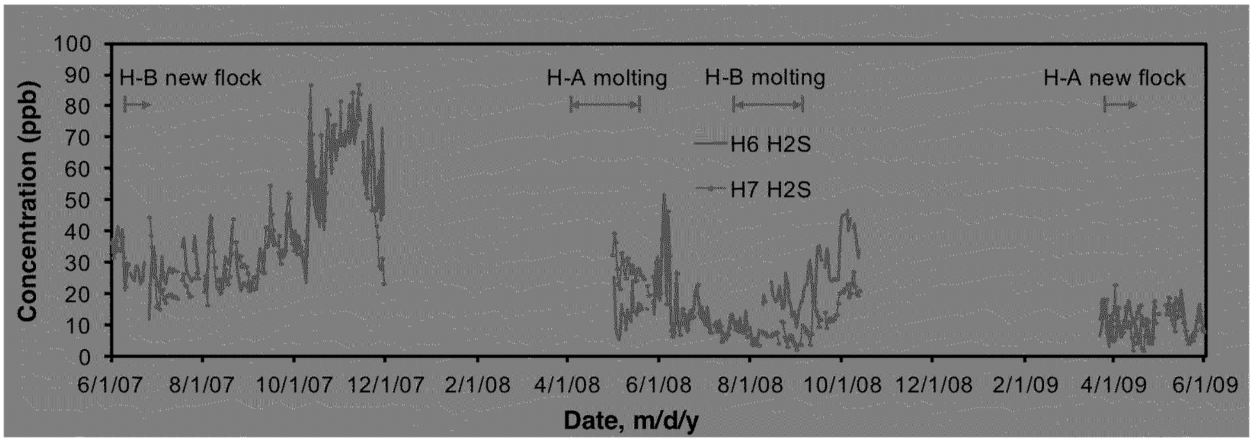

Figure 4.19. Daily mean hydrogen sulfide concentrations at house exhaust at IN2H.

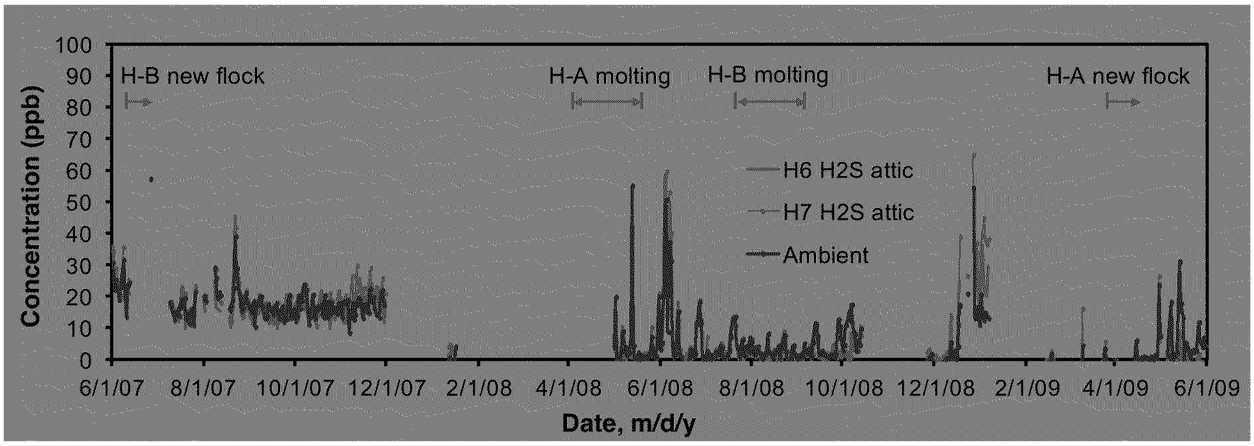

Figure 4.20. Daily mean hydrogen sulfide concentrations in house inlet (attic) and ambient air.

Table 4.104.11 lists characteristics H_2S emissions from both houses in different units. The valid days for house H_2S emissions were 290 d for H6 and 298 d for H7. Like in the NH_3 emission calculation, the valid days for LM- and hen-specific were fewer.

The 2-yr ADM house H_2S emissions were 321±158 and 299±214 g/d for H6 and H7, respectively. Emission between the two houses were not statistically different (P>0.05). However, these two emission rates did not have significant statistical difference (P>0.05).

The 2-yr ADM H_2S emissions per animal unit were 508±229 mg/d-AU from H6 and 462±318 mg/d-AU from H7. Emissions from the two houses were not statistically different (P>0.05). Hen-specific emissions ranged from 0.0 to 10.1 mg/d-hen and averaged 1.5±0.9 mg/d-hen for H6. They ranged from 0.1 to 5.7 mg/d-hen and averaged 1.3±0.9 mg/d-hen for H7. Like the AU-specific emissions, the hen-specific emissions were not statistically different between the two houses either (P>0.05). Figure 4.21through Figure 4.23 illustrate the variations of daily mean H_2S emissions, normalized to different units, from both houses.

Table 4.10. Summary of hydrogen sulfide emissions from IN2H.

Parameter	Per house, g/d		Per AU, mg/d-AU		Per hen, mg/d-hd	
	H6	H7	H6	H7	H6	H7
2-yr valid days	284	286	279	286	284	286
Minimum DM	13	11	64	16	0.0	0.1
Maximum DM	853	1305	1286	1901	10.1	5.7
1st yr ADM±SD	372±150	428±234	563±219	645±345	1.6±0.7	1.9±1
2nd yr ADM±SD	279±152	184±99	461±227	298±169	1.4±1	0.9±0.4
2-yr ADM±SD	321±158	299±214	508±229	462±318	1.5±0.9	1.3±0.9

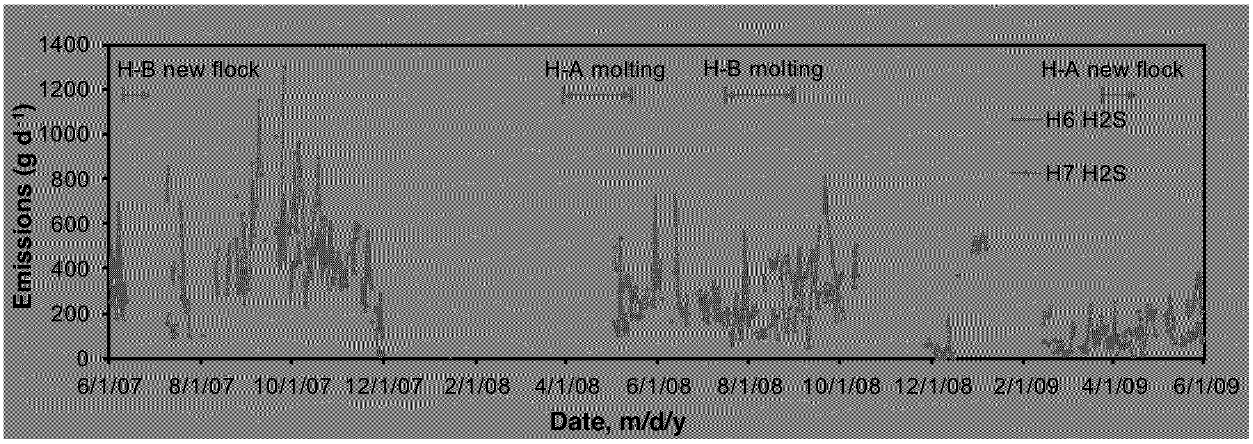

Figure 4.21. Daily mean hydrogen sulfide house emission at IN2H.

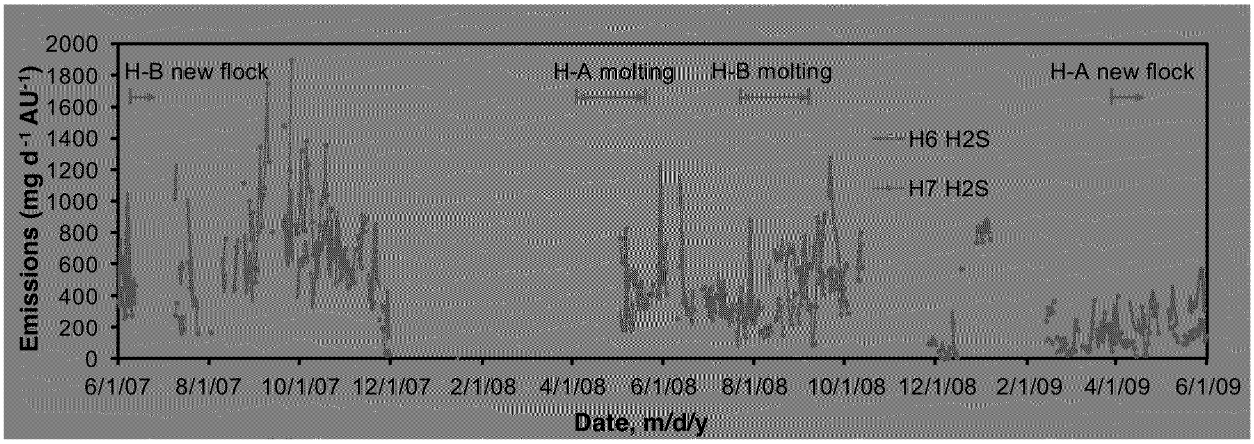

Figure 4.22. Daily mean LM-specific hydrogen sulfide emission at IN2H.

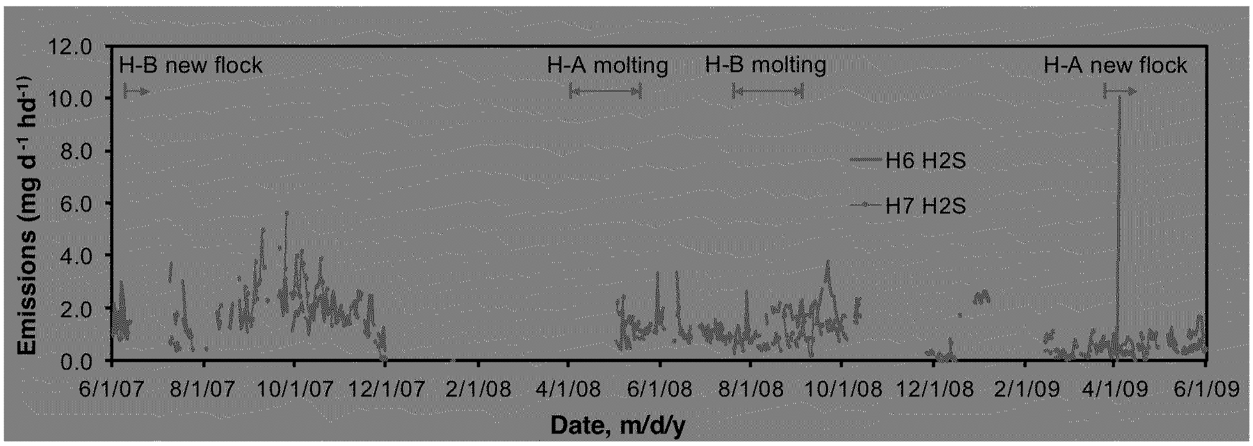

Figure 4.23. Daily mean hen-specific hydrogen sulfide emission at IN2H.

Correlation coefficients for hen-specific H_2S emissions and various possible influencing factors are given in Table 4.12. Hydrogen sulfide emissions were positively correlated with temperature, egg production and LMD and negatively correlated with hen age.

Table 4.13. Correlations between area-specific PM_{10} emission and various factors.

Parameter	Averaging Interval	r
Inlet Temp	Daily	0.426
Eggs	Daily	0.425
Ventilation	Daily	0.394
LMD	Daily	0.385
Exhaust Temp	Daily	0.376
Inlet Temp	Hourly	0.364
Ventilation	Hourly	0.344
Exhaust Temp	Hourly	0.330
LMD	Hourly	0.288
Exhaust RH	Hourly	0.203
Hen Activity	Hourly	0.101
Solar	Hourly	0.074
Time of Day	Hourly	0.037
Exhaust RH	Daily	0.028*
Wind Speed	Hourly	0.001*
Static Pressure	Hourly	-0.000*
Atmospheric Pressure	Hourly	-0.038
Hen Age	Hourly	-0.397
Hen Age	Daily	-0.467

Note: n= 18,030 to 18,116 and 594-695 for hourly and daily means, respectively.

Multiple linear regression showed thermal variables accounted for most of the variance in hourly means whereas flock characteristics followed by thermal factors dominated the daily mean variance (Table 4.14).

Exhaust temperature and LMD accounted for 17 and 24% of the hourly and daily mean H2S emissions, respectively (Equations 4.3 and 4.4).

Hourly: $E = -197.9 + 2.95\ T + 3.33\ D$, $R^2 = 0.17$ (4.3)

Daily: $E = -283.3 + 3.00\ T + 4.891\ D$, $R^2 = 0.24$ (4.4)

Table 4.14. Parameters influencing area-specific hydrogen sulfide emission.

Hourly Means of H_2S Emissions		Daily Means of H_2S Emissions	
Parameter	**R^2**	**Parameter**	**R^2**
Exhaust RH * Atmospheric Pressure	0.324	LMD	0.485
Exhaust Temp * Atmospheric Pressure	0.433	Hen Age * Exhaust Temp	0.470
Exhaust RH * Static Pressure	0.485	Inlet Temp * Ventilation	0.486
Exhaust Temp * Static Pressure	0.547	Exhaust Temp * Ventilation	0.506
Exhaust RH	0.557	Exhaust RH * Ventilation	0.515
Static Pressure	0.565	Eggs * LMD	0.517
Atmospheric Pressure * Static Pressure	0.575	Exhaust Temp * Exhaust RH	0.522
Exhaust Temp * Exhaust RH	0.581	Ventilation	0.525
Ventilation * Exhaust Temp	0.584	LMD * Ventilation	0.533
Time of Day * Wind Speed	0.593	Eggs * Exhaust Temp	0.535
Ventilation * Wind Speed	0.598	Inlet Temp	0.538
Inlet Temp * Static Pressure	0.599	Hen Age * Inlet Temp	0.543
Inlet Temp * Exhaust Temp	0.601	Eggs * Hen Age	0.546
Inlet Temp * Atmospheric Pressure	0.603		
Time of Day * Atmospheric Pressure	0.611		
Time of Day	0.616		
Inlet Temp	0.618		
Wind Speed * Hen Activity	0.620		
Exhaust Temp	0.621		
Inlet Temp * Wind Speed	0.621		
Exhaust RH * Wind Speed	0.626		
Exhaust RH * Solar	0.627		
Inlet Temp * Solar	0.629		
Inlet Temp * Exhaust RH	0.630		
Exhaust Temp * Wind Speed	0.630		

4.3.5. Carbon Dioxide Concentration and Emissions

Valid days for CO_2 concentrations was 619 d for ambient background air, 608 d for H6 inlet, and 608 d for H7 inlet (Table 4.154.13). The daily mean concentrations ranged from 369 to 956 ppm for the background and house inlet air. The 2-yr ADM CO_2 concentrations were 531±63 ppm for background, 478±35 ppm for H6 inlet, and 511±53 ppm for H7 inlet. The inlet concentration at the H7 was lower than that of the H6. However, no statistically significant difference was observed (P>0.05). The DM CO_2 concentrations at ambient and house air inlets show that they follow the seasonal patterns (Figure 4.24). This was probably due to the circulation of exhaust air back to the house inlets. Concentrations of CO_2 from the house exhaust air were much higher in winter than in summer (Figure 4.25).

Table 4.15. Summary of carbon dioxide concentrations (in ppm) at IN2H.

Parameter	Ambient	H6 Inlet	H7 Inlet	H6 Exhaust	H7 Exhaust
2-yr valid days	619	608	595	605	612
Minimum DM	417	369	406	596	522
Maximum DM	956	826	825	3763	4064
1st yr ADM±SD	536±69	477±36	513±48	1711±827	1781±910
2nd yr ADM±SD	525±55	480±35	509±58	1804±869	1830±859
2-yr ADM±SD	531±63	478±35	511±53	1755±848	1804±887

The number of valid days of CO_2 concentrations obtained at the pit exhausts were 605 d and 612 d for H6 and H7, respectively. The DM CO_2 concentrations ranged from 522 ppm in summer to 4064 ppm in winter, both were detected in H7 (Table 4.154.13 and Figure 4.25). The 2-yr mean concentrations in the high-rise houses (1755±848 ppm in H6 and 1804±887 ppm in H7) at this site were 80% of those in the IN2B site (2295±871 ppm in H8 and 2285±946 ppm in H9). However, the CO_2 concentrations between the exhausts of H6 and H7 were not statistically different ($P>0.05$). The maximum daily mean CO_2 concentrations in the high-rise houses were also generally lower than in the manure-belt houses. However, compared with NH_3, the differences in CO_2 concentrations between the two house types were less extensive.

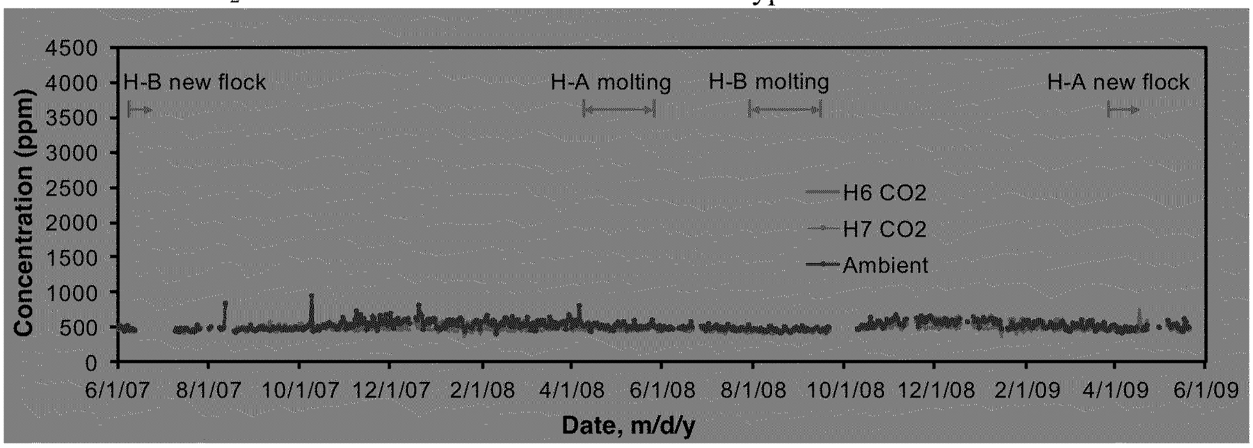

Figure 4.24. Daily mean carbon dioxide concentrations at house inlets (attic) and ambient air.

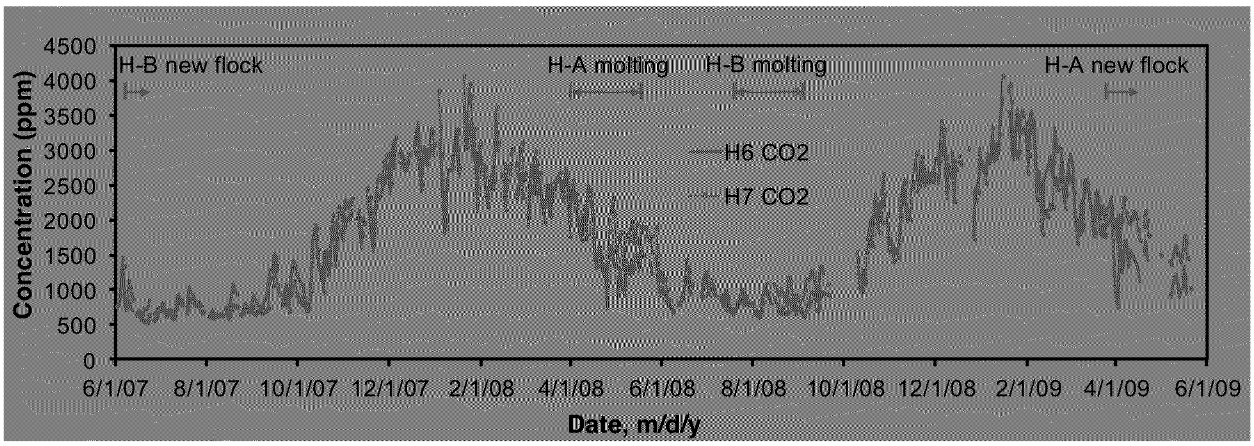

Figure 4.25. Daily mean carbon dioxide concentrations at house exhaust at IN2H.

The patterns of seasonal CO_2 concentration variations were very similar to those of NH_3 in both houses. The high daily mean concentrations were detected between January and March. July and August were the months with the lowest CO_2 concentrations. The layer hen house CO_2 exhibited wide range of DM concentrations and differed from some reported values of 758 ppm in exhaust air (Dobeic and Pintaric, 2011); and 3072 ppm in winter and 1012 ppm in summer in four manure-belt houses, and 2433 ppm in winter and 520 ppm in summer in four high-rise houses, all with one 20- to 24-h measurement per house per season (Green et al., 2009).

Valid days for CO_2 emissions were lower than those of CO_2 concentrations (Table 4.114.14). They varied from 529 d to 542 d depending on the emission units calculated. No statistical difference in CO_2 emissions between the two houses for all the emission units listed in Table 4.114.14.

Table 4.11. Summary of carbon dioxide emissions from IN2H.

Parameter	Per house, kg/d		Per AU, kg/d-AU		Per hen, g/d-hen	
	H6	H7	H6	H7	H6	H7
2-yr valid days	542	529	537	524	529	540
Minimum DM	1226		15290	16766	256	44.7
Maximum DM	26389	31105	43680	86844	5151	127.0
1st yr ADM±SD	16957±2681	18064±4712	26244±4656	28807±7149	2991±780	74.7±12.6
2nd yr ADM±SD	15808±2898	15730±2281	26134±3537	24713±3268	2605±378	76.4±11.2
2-yr ADM±SD	16402±2846	16970±3948	26191±4159	26870±6013	2810±654	75.5±12

Emissions of CO_2 from the two IN2H houses exhibited seasonal patterns. They were slightly lower in summers and higher in spring (Figure 4.26 to Figure 4.28). The peaks of CO_2 emissions occurred from March to April 2008. During empty days between the flocks in both houses, the emission of CO_2 went down to close to zero (Figure 4.26), demonstrating that CO_2 was mainly produced by the hens. The emission of CO_2 was also greatly reduced molt.

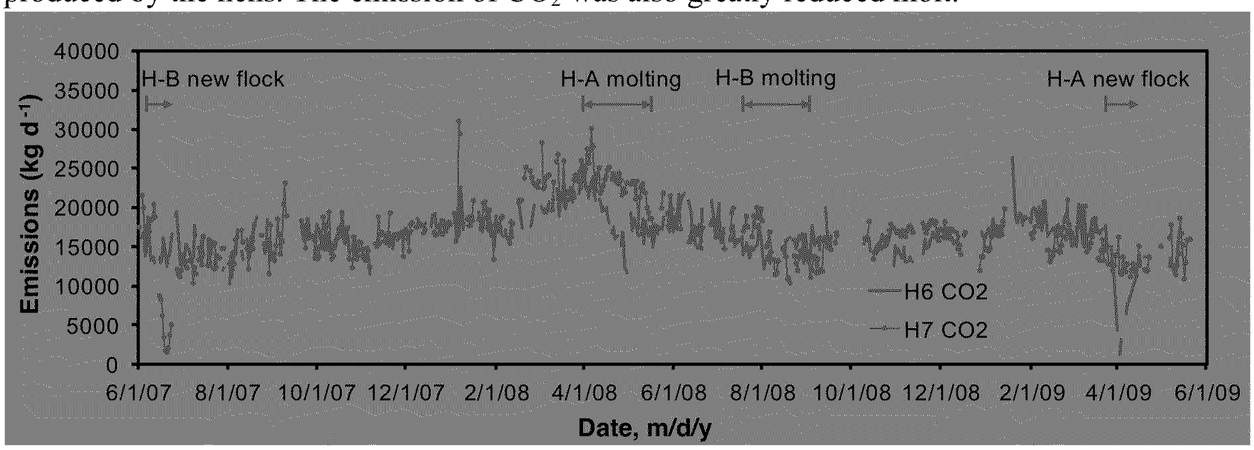

Figure 4.26. Daily mean carbon dioxide house emission at IN2H.

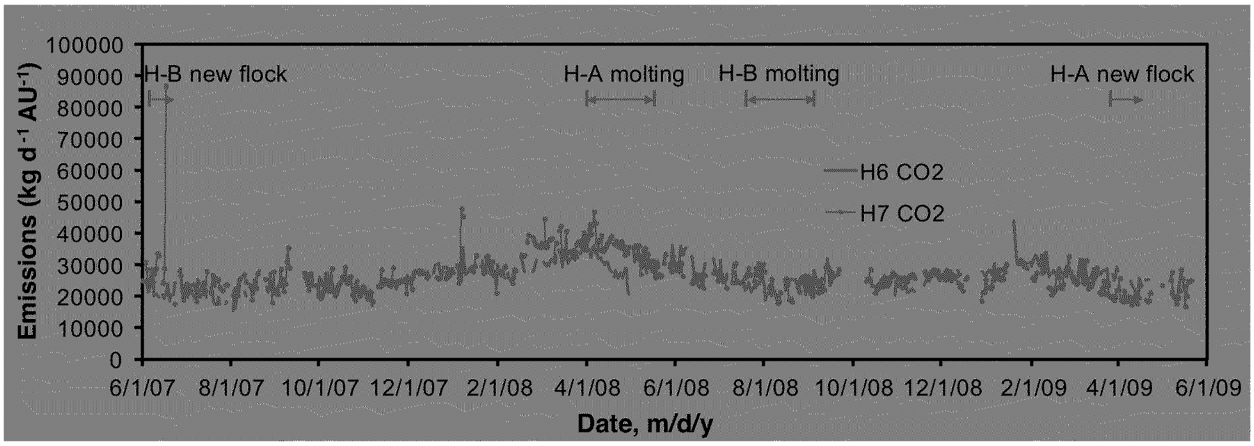

Figure 4.27. Daily mean LM-specific carbon dioxide emission at IN2H.

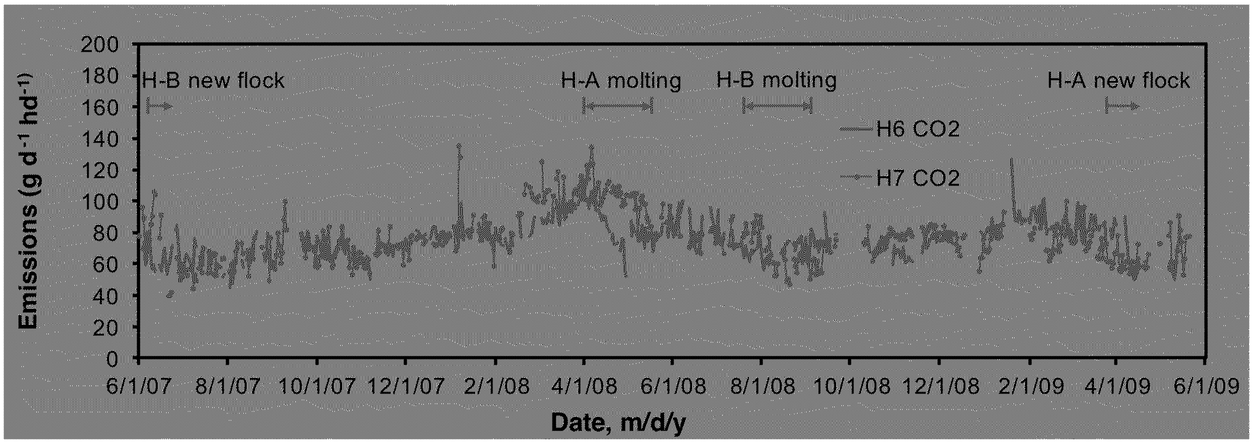

Figure 4.28. Daily mean hen-specific carbon dioxide emission at IN2H.

Single factor analysis of full houses showed that hen activity was most highly correlated with hourly CO_2 emissions in a positive way . Emissions were obviously diurnally related since indirect effects solar energy and static pressure were top factors, both of which are related to temperature. This table shows conclusively that CO_2 emissions decrease with temperature and increase with flock inventory, activity and production.

Table 4.17. Correlations between area-specific CO_2 emission and various factors (*p>0.05).

Parameter	Averaging Interval	r
Hen activity	Hourly	0.327
Solar	Hourly	0.168
Eggs	Daily	0.133
Wind speed	Hourly	0.113
Exhaust RH	Hourly	0.105
Exhaust RH	Daily	0.103
LMD	Hourly	0.079
Time of day	Hourly	0.068
LMD	Daily	0.016*
Hen age	Daily	0.009*
Hen age	Hourly	0.007
Exhaust temp	Hourly	0.005*
Ventilation	Hourly	-0.007
Atmospheric pressure	Hourly	-0.061
Exhaust temp	Daily	-0.093
Inlet temp	Hourly	-0.121
Ventilation	Daily	-0.218
Inlet temp	Daily	-0.226
Static pressure	Hourly	-0.321

Note: n= 25730 to 27203 and 913-942 for hourly and daily means, respectively.

The multiple linear regression showed exhaust temperature with its associated variables having a predominant role in accounting for the variation in CO_2 emissions, especially for daily means (Table 4.18). The house effect was the third most important factor. Atmospheric pressure accounted for the most variation in hourly means but was not included in the analysis of daily means because of its obvious interaction with direct factors. The top flock factor was hen age as it appeared in the second term for hourly means, but it appeared in the eighth term for daily means as thermal factors dominated.

Table 4.18. Parameters influencing area-specific carbon dioxide emissions.

Hourly Means of CO_2 Emissions		Daily Means of CO_2 Emissions	
Parameter	**R^2**	**Parameter**	**R^2**
Atmospheric Pressure	0.283	Inlet Temp * Ventilation	0.060
Exhaust Temp * Hen Age	0.462	Exhaust Temp * Ventilation	0.458
House	0.513	House	0.477
Exhaust Temp * Static Pressure	0.564	Exhaust Temp	0.480
Static Pressure	0.592	Ventilation	0.486
Hen Age	0.612	Inlet Temp	0.497
Exhaust RH * Static Pressure	0.624	Inlet Temp * Exhaust Temp	0.500
Exhaust RH	0.634	Eggs * Hen Age	0.501
Wind Speed * Hen Age	0.644	Inlet Temp * Exhaust RH	0.506
Wind Speed * Static Pressure	0.646	Hen Age * Inlet Temp	0.509
Exhaust RH * Atmospheric Pressure	0.647	Hen Age * Exhaust Temp	0.512
Inlet Temp * Hen Age	0.651	LMD	0.513
Static Pressure * Hen Age	0.652	Eggs * Inlet Temp	0.514
Static Pressure * Hen Activity	0.654	LMD * Hen Age	0.516
Hen Activity	0.658	Eggs	0.517
Exhaust Temp * Wind Speed	0.659	Eggs * LMD	0.540
Exhaust RH * Hen Activity	0.661	Eggs * Exhaust Temp	0.545
Exhaust Temp * Hen Activity	0.664	LMD * Exhaust Temp	0.547
Atmospheric Pressure * Hen Activity	0.666	LMD * Inlet Temp	0.549
Atmospheric Pressure * Wind Speed	0.666	Hen Age * Ventilation	0.555
Wind Speed	0.667		
Exhaust Temp	0.669		

Exhaust temperature and LMD fared poorly in predicting CO_2 for both hourly and daily means. Exhaust temperature was not significant for hourly emissions and LMD was insignificant for daily means (Equations 4.5 and 4.6).

Hourly: $E = 1714 + 20.49\ D, \quad R^2 = 0.01$ (4.5)

Daily: $E = 3106 - 13.18\ T, \quad R^2 = 0.01$ (4.6)

4.3.6. Correlations among Gaseous Pollutants

Correlations among gaseous pollutants are given in Table 4-124.16. In general, the strongest correlations (r values of 0.671 and 0.606 in H6 and H7, respectively) were between CO_2 and NH_3, the two aerobically-produced gases. Hydrogen sulfide (H_2S), an anaerobic gas, was not correlated, or only weakly so, with NH_3 or CO_2. PM_{10} was almost always negatively correlated with all of the gases.

Table 4-12. Correlations between hen-specific emissions of four pollutants.

Parameter	NH_3	H_2S	CO_2
House 6			
NH_3	-		
H_2S	-0.032	-	
CO_2	0.671	-0.057	-
PM_{10}	-0.270	-0.263	0.094
House 7			
NH_3	-		
H_2S	0.087	-	
CO_2	0.606	0.113	-
PM_{10}	-0.431	-0.221	-0.271

4.3.7. PM_{10} Concentration and Emission

Because the TEOM was originally designed for measuring relatively low ambient PM concentrations, it was more susceptible to errors and failures when used in high PM concentration environments such as in the layer hen houses. A total of 411 valid days of PM_{10} concentrations were measured in each house, and 496 d for the ambient location (Table 4-204.17). The lower valid days for PM_{10} measurement, compared with other pollutants, was because of more frequent failure of the TEOMs, and to their sometimes being dedicated to other PM measurements (TSP and $PM_{2.5}$). The 2-yr ADM concentrations in H6 (540±303 μg/m^3) and in H7 (552±338 μg/m^3) were statistically similar (P>0.05).

Table 4-20. Summary of PM_{10} concentrations at IN2H.

Parameter	Ambient	H6 Exhaust	H7 Exhaust
2-yr valid days, d	496	544	524
Minimum DM, μg/m^3	5.7	1.3	2.5
Maximum DM, μg/m^3	566.6	1718.6	3270.3
1st yr ADM±SD, μg/m^3	89±50	473±285	443±203
2nd yr ADM±SD, μg/m^3	104±85	616±305	668±408
2-yr ADM±SD, μg/m^3	96±70	540±303	552±338

The daily mean exhaust air PM_{10} concentrations varied considerably between the houses (Figure 4.29). The seasonal variations of PM_{10} concentrations were not obvious as gas concentrations at this site. However, distribution of the valid days in Figure 4.29 shows that missing data days were not as many as at IN2B site and did not affect the 2-yr mean concentrations in the two houses. Therefore, concentrations in the two houses were not statistically different (P>0.05).

Dust concentrations in poultry houses vary greatly. Ellen et al. (2000) summarized ranges from 10 to 6500 μg m^{-3} for respirable dust (roughly equivalent to PM_{10}). Houses with caged layer hens showed the lowest dust concentrations, compared with the other housing systems. Ellen et al. (2000) also discussed the factors affecting dust concentrations, including animal category, animal activity, bedding material, and season. The 2-yr mean PM_{10} concentrations at this site were in the lower end of the range reported by Ellen et al. (2000), and also lower than the 840 μg m^{-3} respirable particle concentrations obtained in a survey by Banhazi et al. (2008).

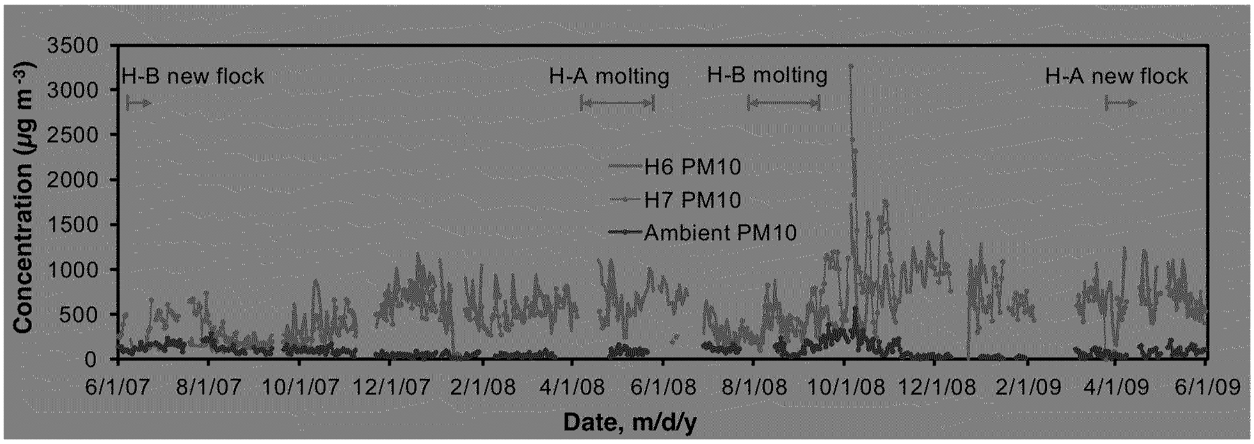

Figure 4.29. Daily mean PM_{10} concentration at IN2H.

Valid days for PM_{10} emissions ranged from 384 to 411 d depending on the emission units (Table 4-214.18). The negative minimum emission rates were due to the effect of humidity changes in the air sample that introduced measurement variations. Fluctuations in DM emission rates in different units did not show regular patterns that can be applied to both houses. For example, when the emissions from H6 were low from June to August 2007 and from September to November 2008, the emissions were high during the same periods from H7 (Figure 4.30 and Figure 4.32). The house emissions of 3.69±3.20 kg/d from H6 and 4.93±3.98 kg/d from H7 indicated statistical differences ($P<0.05$). The LM- and hen-specific emissions were also statistical different ($P<0.05$).

Table 4-21. Summary of PM_{10} emissions from IN2H with different units.

Parameter	Per house, g/d		Per AU, g/d-AU		Per hen, mg/d-hen	
	H6	H7	H6	H7	H6	H7
2-yr valid days	411	403	407	399	411	403
Minimum DM	-7678	-1265	-11.35	-17.07	-33.20	-53.33
Maximum DM	15050	24746	25.31	38.88	86.30	398.00
1st yr ADM±SD	2478±2313	4018±3933	4±3.8	6.5±7.5	11±10	21±34
2nd yr ADM±SD	5051±3495	5919±3795	8.3±5.7	9.7±6.5	24±16	28±18
2-yr ADM±SD	3687±3197	4934±3982	6.0±5.3	8.0±7.2	17±15	24±28

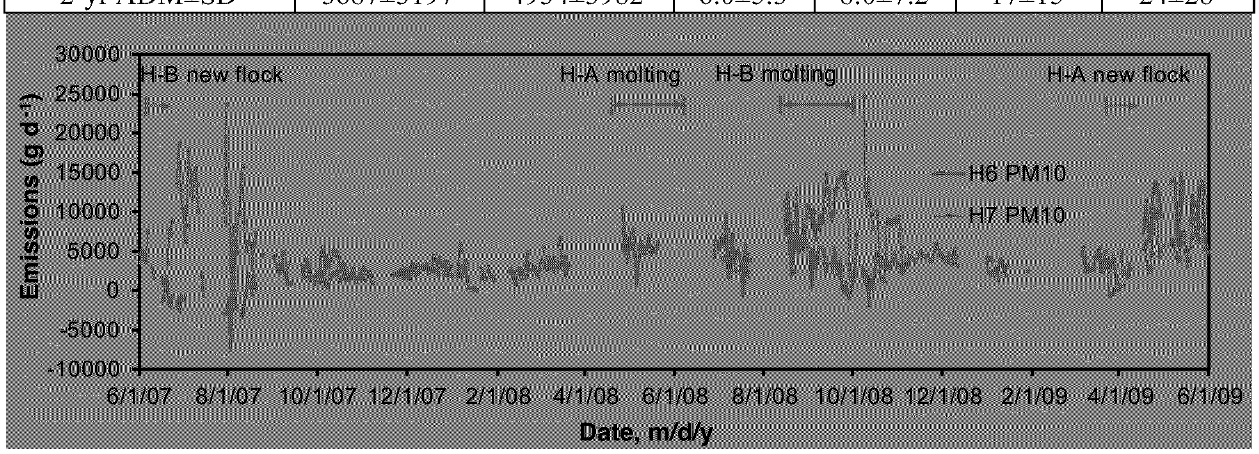

Figure 4.30. Daily mean PM_{10} house emission rate at IN2H.

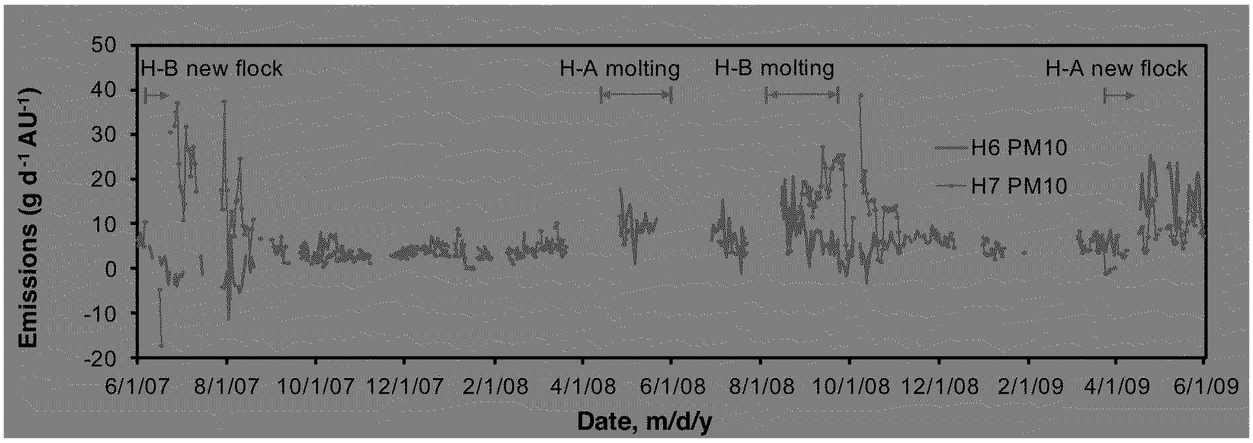

Figure 4.31. Daily mean LM-specific PM_{10} emission rate at IN2H.

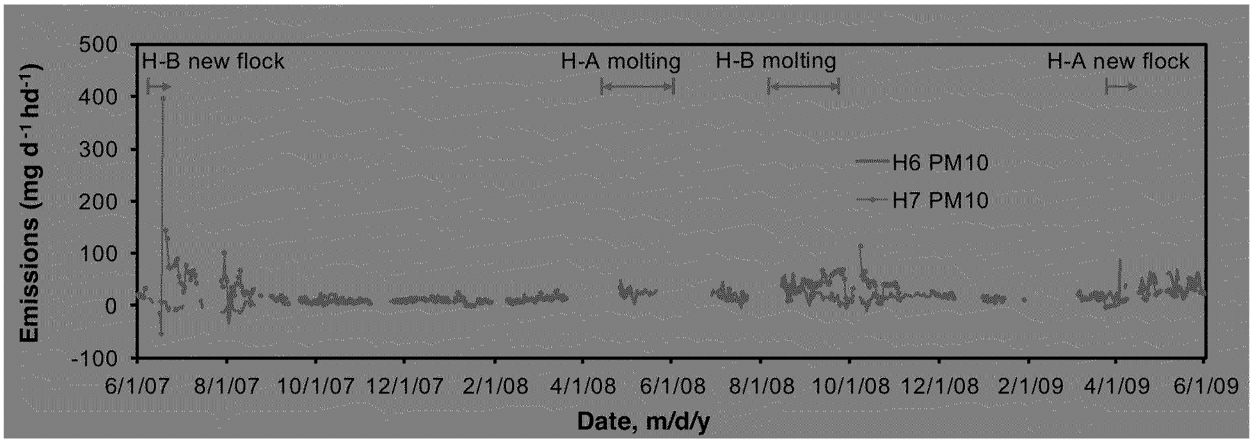

Figure 4.32. Daily mean hen-specific PM_{10} emission rate at IN2H.

The PM_{10} emissions were positively correlated with temperature-related factors, and negatively related to egg production and LMD (Table 4.22). The consistently strong negative effect of inventory was probably due to more active younger hens generating more PM.

Table 4.22. Correlations between area-specific PM_{10} emission and various factors.

Parameter	Averaging Interval	r
Solar	Hourly	0.233
Inlet temp	Daily	0.231
Inlet temp	Hourly	0.203
Ventilation	Daily	0.198
Ventilation	Hourly	0.188
Exhaust temp	Daily	0.173
Exhaust temp	Hourly	0.168
Hen activity	Hourly	0.110
Time of day	Hourly	0.040
Hen age	Hourly	0.033
Wind speed	Hourly	0.018
Atmospheric pressure	Hourly	0.006
Hen age	Daily	-0.010*
Exhaust RH	Hourly	-0.087
Static pressure	Hourly	-0.231
Exhaust RH	Daily	-0.241
LMD	Hourly	-0.326
LMD	Daily	-0.433
Eggs	Daily	-0.645

Note: n= 18,390-19,849 and 710-722 for hourly and daily means, respectively.

Multiple linear regression showed significant differences between full houses and that the thermal and flock related factors seemed equally important in accounting for the variance in PM_{10} emissions (Table 4.23). Egg production, which was not included in hourly mean analysis since hourly egg production was unavailable, accounted for most of the variation in daily mean PM_{10} emissions.

Exhaust temperature and LMD accounted for 14 and 25% of the hourly and daily mean PM_{10} emissions, respectively (Equations 4.7 and 4.8).

Hourly: $E = 5653 - 113.4\ D + 45.89\ T, \quad R^2 = 0.14 \quad (4.7)$

Daily: $E = 6403 - 125.17\ D + 40.64\ T, \quad R^2 = 0.25 \quad (4.8)$

Table 4.23. Parameters influencing area-specific PM_{10} emission.

Hourly Means of PM_{10} Emissions		Daily Means of PM_{10} Emissions	
Parameter	**R^2**	**Parameter**	**R^2**
House	0.281	Eggs	0.418
Exhaust RH * Hen Age	0.340	Inlet Temp	0.441
Time of Day * Ventilation	0.410	House	0.479
Hen Activity * LMD	0.426	Exhaust RH	0.483
Time of Day * Static Pressure	0.435	Eggs * Live Mass Density	0.491
Time of Day * Solar	0.441	Hen Age * Exhaust RH	0.499
Hen Activity	0.443	LMD * Exhaust RH	0.521
Atmospheric Pressure * Hen Activity	0.444	Eggs * Hen Age	0.523
Inlet Temp	0.446	Hen Age * Inlet Temp	0.526
Atmospheric Pressure * LMD	0.447	Hen Age * Ventilation	0.532
Inlet Temp * LMD	0.470	Inlet Temp * Ventilation	0.543
Time of Day * Inlet Temp	0.474	Ventilation	0.550
Solar * Hen Age	0.478	LMD * Ventilation	0.561
Solar * Hen Activity	0.479	Eggs * Exhaust Temp	0.564
Solar * LMD	0.480	Eggs * Ventilation	0.565
Exhaust Temp * Solar	0.482	LMD * Exhaust Temp	0.568
Inlet Temp * Hen Activity	0.484	Exhaust Temp	0.570
Hen Activity * Hen Age	0.485	Exhaust RH * Ventilation	0.572
Time of Day * Hen Age	0.486	Exhaust Temp * Exhaust RH	0.576
Ventilation	0.486		
Ventilation * Atmospheric Pressure	0.486		
Exhaust RH * Static Pressure	0.487		

4.3.8. $PM_{2.5}$ Concentration and Emission

Only 43 valid days were obtained during the monitoring of $PM_{2.5}$ at the background air in the two years (Table 4-244.20 and Figure 4.33). For exhaust $PM_{2.5}$ concentrations, the valid days were 41 for H6 in the two years and 24 for H7 in year one. The DM concentrations ranged from -5 to 212 μg/m^3. The highest DM concentration was detected in the H6 exhaust. The ADM concentrations were 18.9±19.6 μg/m^3 for ambient air, 46.4±31.8 μg/m^3 for H6, and 40.4±37.9 μg/m^3 for H7. The exhaust concentrations between the two houses were not statistically different (P>0.05).

Table 4-24. Summary of $PM_{2.5}$ concentrations at IN2H.

Parameter	Ambient	H6 Exhaust	H7 Exhaust
2-yr valid days, d	43	41	24
Minimum DM, μg/m^3	-5	16	-1
Maximum DM, μg/m^3	117	212	192
1st yr ADM±SD, μg/m^3	20.7±14.5	34.6±8.2	40.4±37.9
2nd yr ADM±SD, μg/m^3	16.9±24.1	75±46.3	
2-yr ADM±SD, μg/m^3	18.9±19.6	46.4±31.8	40.4±37.9

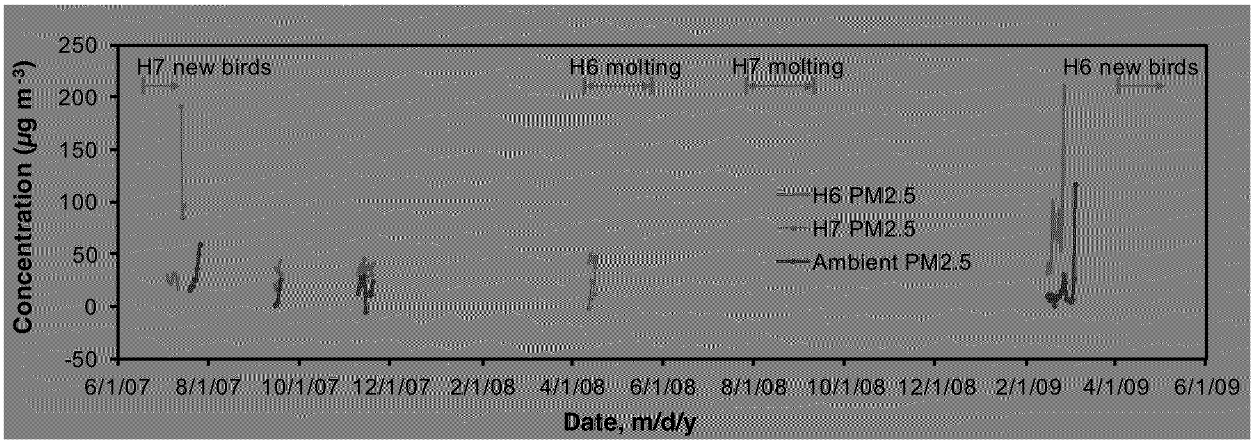

Figure 4.33. Daily mean $PM_{2.5}$ concentration at IN2H.

For valid days of $PM_{2.5}$ emissions, only 22 d in H6 for (for two years) and 10 in H7 (for year 1) were available (Table 4-274.23 and Figure 4.34 to Figure 4.36). House $PM_{2.5}$ emissions ranged from 37 to 917 g/d. The 2-yr ADM emissions were 232±186 g/d from H6 and 104±49 g/d from H7. The two houses emitted significantly different $PM_{2.5}$ ($P<0.05$). The LM-specific and hen-specific ADM emissions exhibited statistical differences.

Table 4-25. Summary of $PM_{2.5}$ emissions at IN2H with different units.

Parameter	Per house, g/d		Per AU, g/d-AU		Per hen, mg/d-hd	
	H6	H7	H6	H7	H6	H7
2-yr valid days	22	10	22	10	22	10
Minimum DM	45	37	0	0	0	0
Maximum DM	917	230	2	0	4	1
1st yr ADM±SD	105.8±42.5	104.2±49.1	0.2±0.1	0.2±0.1	0.5±0.2	0.5±0.2
2nd yr ADM±SD	336.5±194.9		0.6±0.3		1.6±1	
2-yr ADM±SD	231.6±186.4	104.2±49.1	0.4±0.3	0.2±0.1	1.1±0.9	0.5±0.2

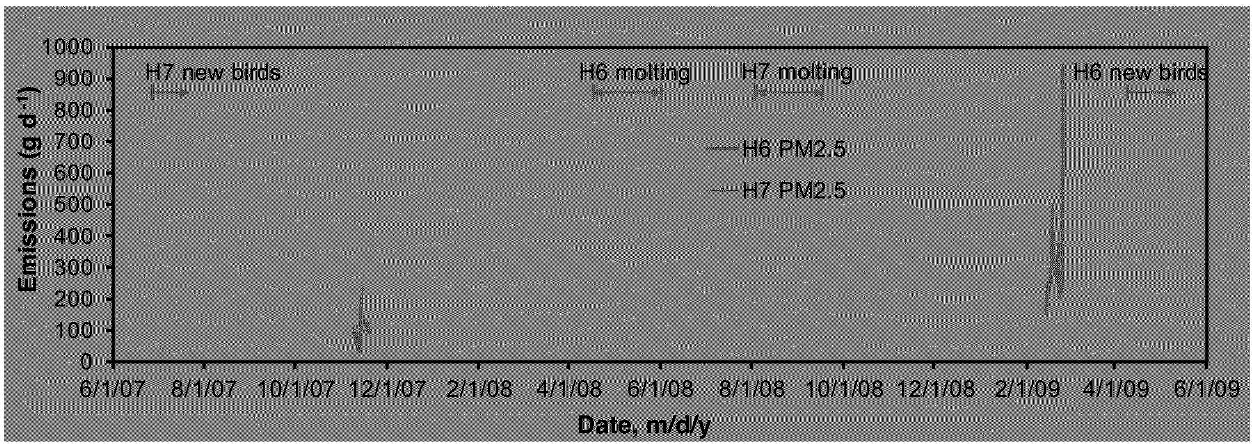

Figure 4.34. Daily mean $PM_{2.5}$ house emission rate at IN2H.

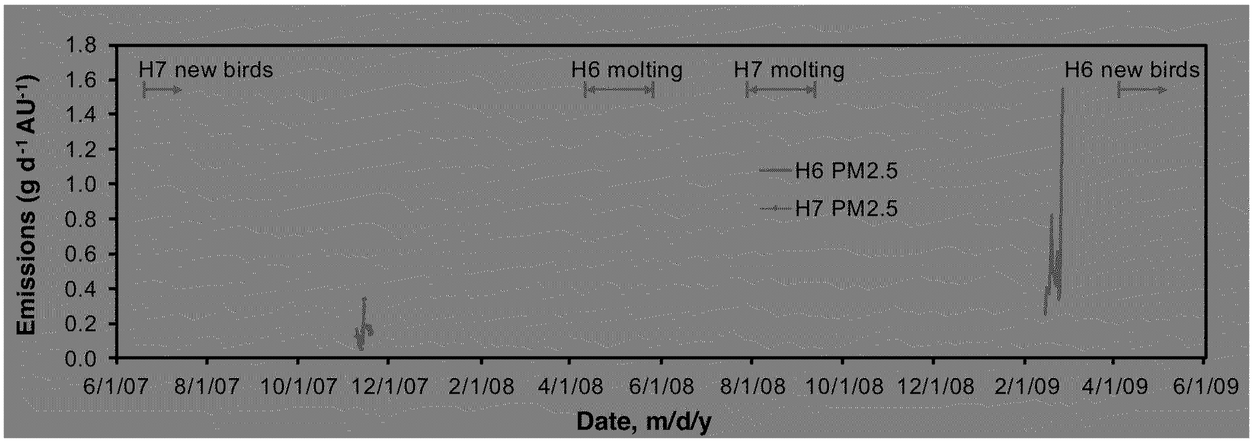

Figure 4.35. Daily mean LM-specific $PM_{2.5}$ emission rate at IN2H.

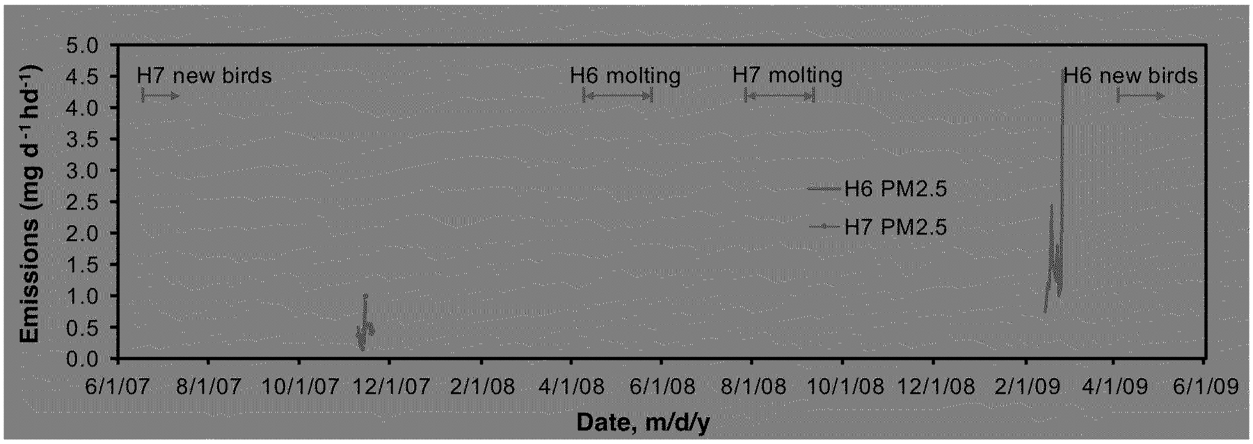

Figure 4.36. Daily mean hen-specific $PM_{2.5}$ emission rate at IN2H.

4.3.9. VOC Concentrations and Emissions

The 20 most prevalent VOCs detected in the canister samples accounted for 9 6% of the total quantified mass. The most prevalent compound was 2-methyl-propenoic acid methyl ester, which was 49% of the total mass (Table 4-134.22). Concentrations of total VOC in exhaust air ranged from 0.52 to 23.5 mg m $^{-3}$ in H6, 0.72 to 4.91 mg m $^{-3}$ in H7. The mean total VOC concentrations were 4.31±8.49 in H6, 2.04±1.89 mg m^{-3} in H7, respectively (Table 4-274.23).

Total VOC emissions (mg s^{-1}) during each sampling period were determined by multiplying the mean building airflow rate (m^3 s^{-1}) by the total mass (mg m^{-3}) and converting to kg d^{-1}. The VOC emission rates of H6 and H7 ranged fro m 4.9 to 95.3 and 4.2 to 68.7 kg d^{-1}, respectively. The mean VOC emission rates from H6 and H7 were 35.9±33.8 and 25.1±27.3 kg d^{-1} or 0.166±0.170 and 0.140±0.17 g d^{-1} hd^{-1} (Table 4-274.23). The values given in this table are corrected from the EPA report which had erroneous concentrations and airflows used in the calculations. The correct results will be submitted to the EPA in a revised final report.

Table 4-13. Average concentration of 20 most prevalent VOCs.

Compound	Conc., $\mu g/m^3$	% of total	Cumulative %
2-Methyl-propenoic acid methyl ester	581	49.38	49.38
Hexane	100	8.49	57.87
Dimethyl disulfide	93.2	7.92	65.79
Indole	78.8	6.70	72.49
Propanoic acid	33.9	2.88	75.37
Pentane	26.6	2.26	77.63
Methyl cyclopentane	25.1	2.14	79.77
Pentanal	24.2	2.06	81.82
Phenol	17.3	1.47	83.29
2-Butanol	17.3	1.47	84.76
Benzaldehyde	15.3	1.30	86.07
2,3-Butanedione	15.3	1.30	87.37
Butanal	15.2	1.29	88.65
o-Xylene	14.3	1.22	89.87
2-Pentanone	14.3	1.21	91.08
4-Methyl-phenol	13.9	1.18	92.27
Heptanal	12.5	1.06	93.33
Nonanal	12.0	1.02	94.35
Octanal	7.4	0.63	94.97
Dimethyl trisulfide	7.3	0.62	95.60
Total	1125	95.60	

Table 4-27. Emission of total VOC for each sampling day at IN2H.

Date	# canisters		Concentration (mg m^{-3})		Airflow (m^3s^{-1})		Emission (kg d^{-1})	
	H6	**H7**	**H6**	**H7**	**H6**	**H7**	**H6**	**H7**
1/9/09	2	2	23.5	4.67	47.0	46.5	95.3	18.8
3/12/09	2	2	1.18	1.18	47.8	43.4	4.9	4.4
4/30/09	2	2	0.63	0.72	187.4	123.2	10.2	7.7
5/9/09	2	2	0.60	0.73	117.7	66.2	6.1	4.2
5/13/09	2	2	1.09	4.91	295.7	141.1	27.8	59.8
5/27/09	2	2	2.68	0.81	340.3	176.7	78.7	12.3
6/23/09	2	2	0.52	1.26	621.5	631.7	28.1	68.7
Mean	2	2	4.3	2.0	236.8	175.5	35.9	25.12

4.3.10. Pollutant Emissions per Dozen Eggs

Pollutant emissions per dozen eggs exhibited the same order of magnitude as IN2B (Table 3-313.27),. If CO_2 is excluded, NH_3 had the largest emission rate per dozen eggs, followed by total VOC, PM_{10}, H_2S, and $PM_{2.5}$ (Table 4.28).

Table 4-14. Emissions per day per dozen egg production for six pollutants at IN2H.

Pollutant	House 6	House 7	Site average
CO_2, g/d-doz	1269	1330	1299
NH_3, g/d-doz	17.26	19.53	18.4
VOC, mg/d-doz	1215	498	857
PM_{10}, mg/d-doz	285	387	336
H_2S, mg/d-doz	24.8	23.4	24.1
$PM_{2.5}$, mg/d-doz	17.92	8.17	13.09

4.4. Uncertainties in Airflow and Emission Rate

The overall average airflows for H6 and H7 were 45±16 $dsm^3\ s^{-1}$ (n=664) and 45±11 $dsm^3\ s^{-1}$ (n= 486), respectively. An average of 4.4 fans operated in all houses at which condition the airflow measurement uncertainty was 25%, based on the fan models.

A fan tester (Gates et al., 2004) was used to test fans in the houses. The traversing method was used to test fans that were inaccessible to the fan tester (Table 4-294.25). A total of 520 and 21 tests were conducted using the fan tester and the traverse method, respectively.

The test data were used to develop equations to calculate airflow as a function of differential pressure and fan rotational speed, and to assess uncertainties in airflow predictions.

Table 4-29. Number of valid fan tests at IN2H.

Test time	House	Fan tester, n	Traverse, n
Aug. 2007	6 and 7	119	
Aug. to Sep. 2008	6	78	7
Oct. to Nov. 2008	7	57	
March to July 2009	6 and 7	266	14
Total		520	21

House ventilation rates were calculated by using the fan operation status, house differential pressures, and fan curves that describe the relationship between fan airflow rates and differential static pressures. The fan reference curves (Aerotech Model AT481Z1CP) were obtained from the Bioenvironmental and Structural Systems (BESS) Lab Project No. 06260 at the University of Illinois at Urbana-Champaign (BESS, 2006). The field fan curves were obtained during in-situ tests using the fan tester and traverse measurements, and the impeller anemometer signals.

Each performance record consisted of airflow (Q1) measured at several static pressures (P1), and at a relatively constant speeds (N1). For each fan type, the BESS fan curve was adjusted to the mean speed (N2) of the fan tests. The new, speed-indexed baseline curves were derived using the first ($Q_2 = Q_1(N_2/N_1)$) and second ($\Delta P_2 = \Delta P_1(N_2/N_1)^{0.5}$) fan laws, where Q_2 is the speed-adjusted BESS fan curve at speed N_2. The speed-corrected airflow prediction model is $Q_4 = (a \cdot \Delta P_4 + b) \cdot (N_4/N_2) \cdot Q_2$, where ΔP_4 and N_4 are measured fan static pressure and speed. For a given test using the portable fan tester or traverse method, the model is $Q_4 = (a \cdot \Delta P_3 + b) \cdot (N_3/N_2) \cdot Q_2$, where ΔP_3 and N_3 are the measured fan static pressure and speed during the fan test, and the fan degradation factor $k = a \cdot \Delta P_3 + b$. The values for the coefficients a and b were those which

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minimized the sum of square differences between Q_4 and Q_3 for all the valid fan tests within a speed regime. The resulting fan models are shown in Table 4-304.26.

Table 4-30. Models and performance degradation factors for IN2H fans.

Fan type	Fan airflow rate as a function of $\triangle P_s$	Degradation factor
Single-speed fans	Q = 2.17062E-05x^3 + 6.56962E-04x^2 + 6.46716E-02x + 1.05565E+01	0.0021x+0.7594
Variable-speed fans	Q=13.3031x+1.2709	0.0021x+0.7594

Note: in the table, Q is the fan ventilation rate, and x is the $\triangle P_s$ across the wall that the specific fan was installed on.

5. DISCUSSION OF NC2B DATA

5.1. Introduction

The purpose of this chapter is to provide further information and analysis of data collected from the North Carolina egg production facility (site NC2B) in addition to the NAEMS report submitted to the EPA on 7/8/10.

Site NC2B was located 110 km (65 mi) northeast of North Carolina State University (Raleigh, NC). The farm consisted of six high-rise houses with a total capacity of 618,000 hens, five shallow-pits, three natural ventilated houses, and an egg processing plant.

Houses 1-4 were tunnel ventilated with curtain backed cages with 394 cm^2/hen (61 in^2/hen) of space for the hens (W36) as they were raised in low-density conditions. The monitored H3 and H4 were built in 2002. Hens were molted according to standard industry practice. They were fed a corn/soy ration, with extra ingredients (crab meal, cookie meal, etc) added based on availability. Descriptive parameters of the houses are given in Table 5.-11.

Table 5-1. Characteristics of houses at the NC2B site.

Descriptive Parameters	Houses 1-4
House inventory	103,000
Number of tiers of cages	4
Numbers of rows of cages	6
House width, m	18 (58 ft)
House length, m	177 (580 ft)
Ridge height, m	8.4 (27.7 ft)
Sidewall height, m	5.5 (18 ft)
House spacing, m	15.2 (50 ft)
Basement depth, m	2.7 (9 ft)
Manure collection method	Loader
Ventilation type	Tunnel
Number of pit circulation fans	21
Number of air inlets	2
Inlet type	Ceiling baffles
Inlet adjustment method	Auto, Cable
Inlet control basis	Temperature and pressure
Controls vendor/manufacturer	PMS
Walls with fans	East, West
Number of exhaust fans	34
Fan diameter, cm	122 (48 in)
Fan spacing, m	0.2 (9 in)
Fan manufacturer	Choretime
# ventilation stages	11
# temperature sensors	8

5.2. Quality Control and Quality Assurance

5.2.1. Carbon Dioxide Concentration

Carbon dioxide concentration was measured using a photoacoustic infrared monitor (INNOVA Model 1412, Innova AirTech Instruments, Ballerup, Denmark). Multipoint calibrations (MPCs) using purified air (CEM zero-grade Cat. # AIO.OCE-T, Praxair, Indianapolis, IN) and two span concentrations were conducted eight times to assess linearity following analyzer maintenance or replacement. All MPCs used CO_2 calibration gases (0, 1000,1500 and 2000 ppm; 0,1000, 2000,2000,4000 with and without humidification using Nafion tubing), which were delivered through a calibration line to the sampling point in H3 using a six-port gas dilutor (Model 4040, Environics, Tolland, CT). The R^2 values of each MPC exceeded 0.998 (Table 5.-22), indicating linearity of instrument response to standard gas between 0 and 2000 or 5000 ppm.

Table 5-2. Multipoint calibration record and results for the CO_2 measurements.

Date	# of points	Span concentration, ppm		R^2
		Minimum	Maximum	
9/11/07	4	0	2000	0.9750
11/11/07	4	0	5000	0.9900
11/13/07	4	0	5000	0.9900
01/28/08	4	0	5000	0.9990
01/28/08	4	0	5000	0.9999
11/18/08	4	0	5000	0.9999
09/15/09	4	0	5000	0.9996
11/12/09	4	0	5000	1.0000

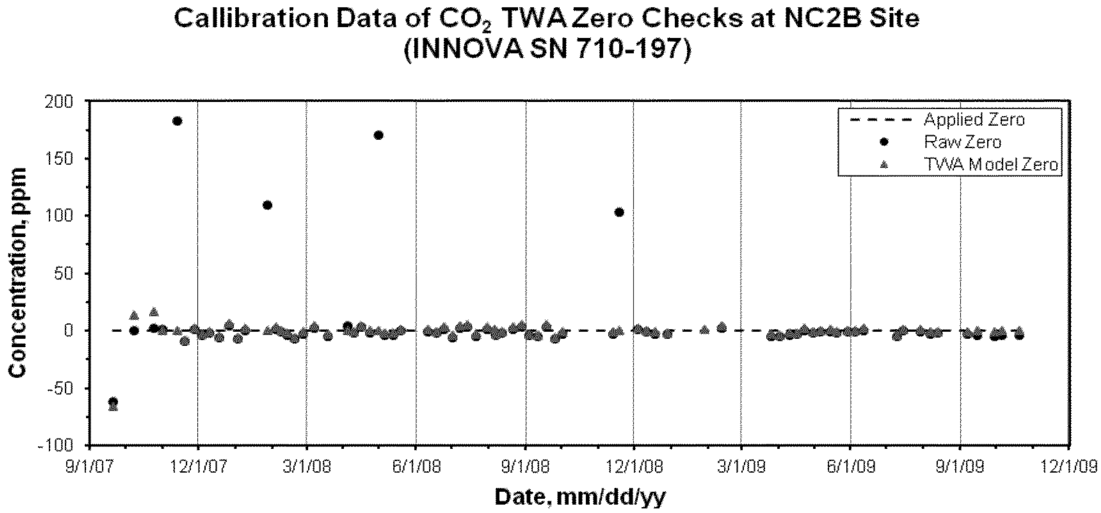
Precision checks were conducted periodically using zero and span gases (Z/S checks), delivered via the dilutor through the challenge line, and responses were recorded to monitor changes in system performance over time. Span checks were conducted with 2000 or 5000 ppm CO_2.

Significant downtime occurred due to factory repair (failed chopper wheel) from 10/23/08 to 11/11/08 and a malfunction after 10/09/09.

The average response of the analyzer to Z/S checks was assessed, and the results were combined based on changes to the instrument or gas sampling system to create linear correction models (Table 5.-33). The models were used to correct instrument readouts. The measurement accuracy was assessed based on model-corrected zero and span checks (Figure 5.1).

Table 5-3. Concentration correction and measurement accuracy for CO_2.

Start/end dates	# of checks		Linear model	Measurement accuracy Relative to Span, %			
				Bias		Precision	
	Zero	Span		z	s	z	s
9/20/07-10/28/07	3	3	y = 1.3x+14.4	0.0	0.0	2.3	0.8
10/28/07-11/21/07	7	7	y = 1.1x-116.0	0.0	0.0	0.1	0.4
11/21/07-1/19/08	6	8	y = 1.1x+1.7	0.0	0.0	0.1	2.4
1/19/08-2/06/08	6	6	y = 1.0x-81.2	0.0	0.0	0.0	0.2
2/6/08-3/21-08	7	7	y= 1.0x+1.5	0.0	0.0	0.1	2.9
3/21/08-10/20/09	40	38	y= 1.0x-2.3	0.0	0.0	0.0	0.7



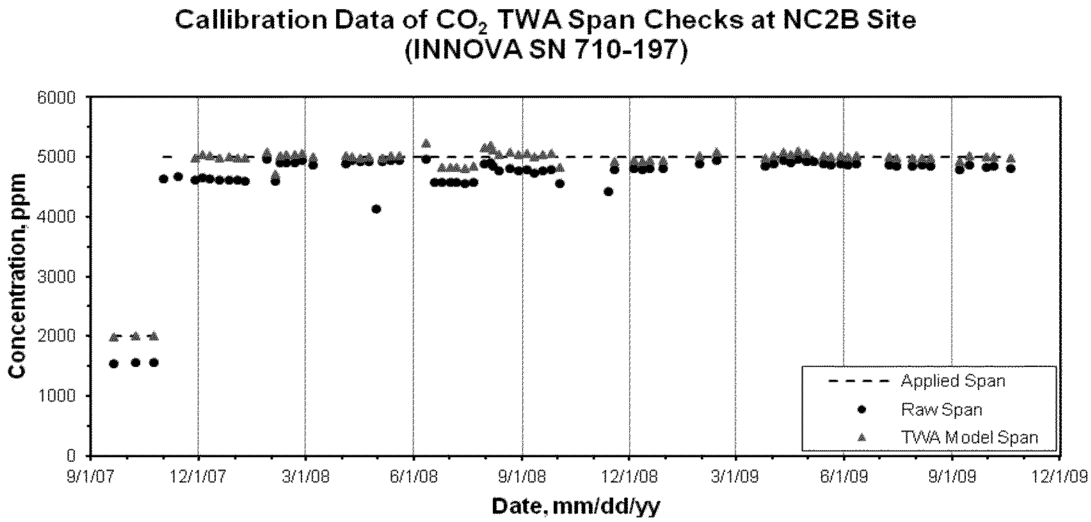


Figure 5.1. Calibration checks of CO_2 measurements.

5.3. Data Analysis

5.3.1. Data Corrections, Substitutions & Calculations

Whenever the QA/QC checks described above indicated a bias in the measurements relative to a standard, the data was corrected prior to its use in emissions calculations.

Emission rates were calculated over a two year period from September 24, 2007 to September 23, 2009. Statistical analysis and correlations, however, were conducted on data collected from September 24, 2007 to December 31, 2009.

5.3.2. Emission per Dozen Eggs Produced

An average daily emission per dozen eggs (egg-specific emission) produced (e.g., g-NH_3/doz) was calculated for each pollutant. Daily egg production was reported by the farm on a house-specific basis; however, there were some days where two days' worth of egg apparently reported on a single day, with zero production reported for the other day.

5.4. Nitrogen Balance Calculation

A nitrogen balance was calculated to compare the inputs and outputs of nitrogen (N) at site NC2B. The calculations were conducted on a house-specific basis, and covered the two full manure accumulation and storage periods (cycles) for which the entire periods were monitored. The only input to the N balance was the feed. Other inputs such as N in the water were not considered. The outputs included total eggs produced, manure produced (storage accumulation), and NH_3 emission. The following considerations were included in the calculations:

- Nitrogen input of the consumed feed was calculated based on ration-specific N in the feed (% wb) and total delivered feed (kg), both of which were daily reported by the farm. The N contents ranged from 1.9 to 3.0%, and were obtained from the farm nutritionist.
- Nitrogen lost in eggs was calculated from the egg N content and the total number of eggs produced. The total egg production was based on producer records. The N content in egg samples ranged from 1.7 to 2.0% and averaged 1.9%.
- Nitrogen content in the manure was calculated from manure production and the average N content (% wb) of manure samples. Manure production was calculated based on daily manure production per hen and house inventories.
- Nitrogen lost in the NH_3 emission was calculated based on the averaged egg-specific emission rate and total egg production.

5.5. Pearson Correlation Coefficient and Multi-Variable Linear Regression

The Pearson correlation coefficients between hourly mean emission rates and other measured variables were calculated using SAS (SAS 9.2, SAS Institute Inc., Cary, NC, USA). While the correlation coefficients assessed linear relationships (and strength) between variables, the analysis was limited. To improve the analyses, multi-variable linear regression was conducted on hourly data. The function used in the SAS procedure was PROC GLMSELECT", with STEPWISE selection of SELECT=CP and CHOOSE=ADJRSQ. Some of the influencing factors analyzed by the procedure included live mass density, hen age, activity, and egg production, airflow rate, inside and outside temperatures and relative humidities, and time of day. Two-way interactions between these variables were also analyzed.

5.6. Results

5.6.1. Animal Characteristics

The occupancies in H3 and H4 averaged 92,954 and 91,320 hens with mean weights of 1.47 and 1.42 kg, respectively (Table 5.-44). Monitoring spanned across two production cycles with clean out periods of about 22 d between flocks. The average egg production of H3 and H4 were 6303 and 5907 doz/d, respectively.

Table 5-4. Monthly means of flock parameters at NC2B.

Month	H3 hens, k hd	H4 hens, k hd	H3 mean wt, kg	H4 mean wt, kg	H3 mean eggs, k	H4 mean eggs, k
Sep. '07	95.3±0.0	92.1±0.0	1.63±0.00	1.49±0.00	88±24.4	81.3±16.5
Oct. '07	95.3±0.0	91.9±0.0	1.63±0.00	1.49±0.00	79.1±39.4	78.4±41.5
Nov '07	95.4±0.0	91.8±0.0	1.64±0.00	1.50±0.00	75.8±27.4	70.8±32.4
Dec. '07	95.4±0.0	91.6±0.0	1.65±0.00	1.50±0.00	75.1±27.9	71.8±25.1
Jan '08	95.4±0.0	91.5±0.0	1.66±0.00	1.51±0.00	71.4±25.6	67.4±24.4
Feb '08	95.5±0.0	91.3±0.0	1.67±0.00	1.51±0.00	69.6±18.3	65.8±17.1
Mar. '08	95.5±0.0	91.2±0.0	1.67±0.00	1.51±0.00	69.4±27.2	65.3±22.1
Apr. '08	20.8±39.4	90.8±0.2	0.41±0.69	1.52±0.00	16.9±26.1	58.8±14.2
May '08	97.8±0.1	90.0±0.2	1.36±0.05	1.54±0.04	47.6±35.4	48.3±31.7
June '08	97.6±0.1	38.2±47	1.42±0.02	0.43±0.61	92.7±13	0.40±1.1
July '08	97.4±0.0	97.0±0.1	1.46±0.01	1.35±0.04	92.8±16.4	63.4±30.3
Aug '08	97.3±0.0	96.8±0.0	1.48±0.01	1.42±0.02	90.9±10.8	90.3±11
Sep. '08	97.2±0.0	96.7±0.0	1.50±0.01	1.47±0.01	88.7±13.3	91.1±14.1
Oct. '08	97.0±0.0	96.5±0.0	1.51±0.01	1.46±0.01	96.9±29.9	98.3±34.4
Nov. '08	96.8±0.3	96.3±0.4	1.48±0.02	1.44±0.01	81.0±39.9	82.2±40.8
Dec. '08	96.7±0.1	96.2±0.3	1.46±0.01	1.42±0.00	81.0±18.3	81.0±16.7
Jan. '09	96.4±0.1	96.1±0.1	1.47±0.00	1.43±0.01	80.1±24.5	82.0±23.8
Feb. '09	96.0±0.1	95.8±0.1	1.46±0.01	1.42±0.01	77.8±21	78.8±21.8
Mar. '09	95.6±0.1	95.5±0.1	1.43±0.01	1.41±0.00	76.8±18.9	78.1±14.9
Apr. '09	95.0±0.2	95.1±0.1	1.31±0.08	1.42±0.01	46.5±29.8	75.0±15.3
May '09	94.6±0.1	94.6±0.2	1.49±0.00	1.43±0.00	67.2±25.3	75.1±15.5
June '09	94.3±0.1	94.0±0.2	1.49±0.01	1.46±0.03	81.2±25.9	73.9±23.9
July '09	94.1±0.1	93.4±0.2	1.52±0.02	1.50±0.00	78.3±29.8	69.7±28.5
Aug. '09	93.8±0.1	92.8±0.2	1.56±0.00	1.50±0.02	76.7±29.2	78.7±41.5
Sep. '09	93.6±0.1	92.2±0.2	1.55±0.00	1.51±0.14	-	-

5.6.2. Environmental Conditions and Airflow

Static pressure distributions for each house are shown in Figure 5.2. The frequency distributions of the differential static pressure across the end walls of H3 and H4 were relatively similar. The average daily static pressure differentials were -17.8±3.6 Pa and -16.9±2.8 Pa in H3 and H4. The median static pressure differential was -20±5 Pa in both houses. The fraction of time that the pressure was positive ranged from 0.1 to 0.5%. It was less than -30 Pa about 90% of the time. Airflow rate, and gas and PM emission data were invalidated under conditions of positive house static pressure, because positive pressure was assumed to have caused numerous other openings in the house. Since this could cause a significant underestimate of airflow leaving the house (and therefore of emissions), this step was seen as necessary to avoid biasing the results. House emissions were only considered valid when there was a negative or underpressure in the house.

The DM exhaust temperatures ranged from 14 to 32°C and the inlet temperature ranged from -6 to 32°C (Figure 5.3 and Table 5.-55). The average DM RH of inlet air and H3 and H4 exhausts were 65.3±11.0, 68.1±8.0, and 67.5±7.8%, respectively. These house humidity levels are typical of layer houses (Figure 5.4). Ventilation rates ranged from 1.8 m^3/s in winter to 263 m^3/s in summer for H3 and from 8.8 m^3/s in winter to 294 m^3/s in summer (Figure 5.5). The hourly mean hen-specific ventilation rates of H3 and H4 were 4.72 and 3.94 $m^3\ h^{-1}$, respectively.

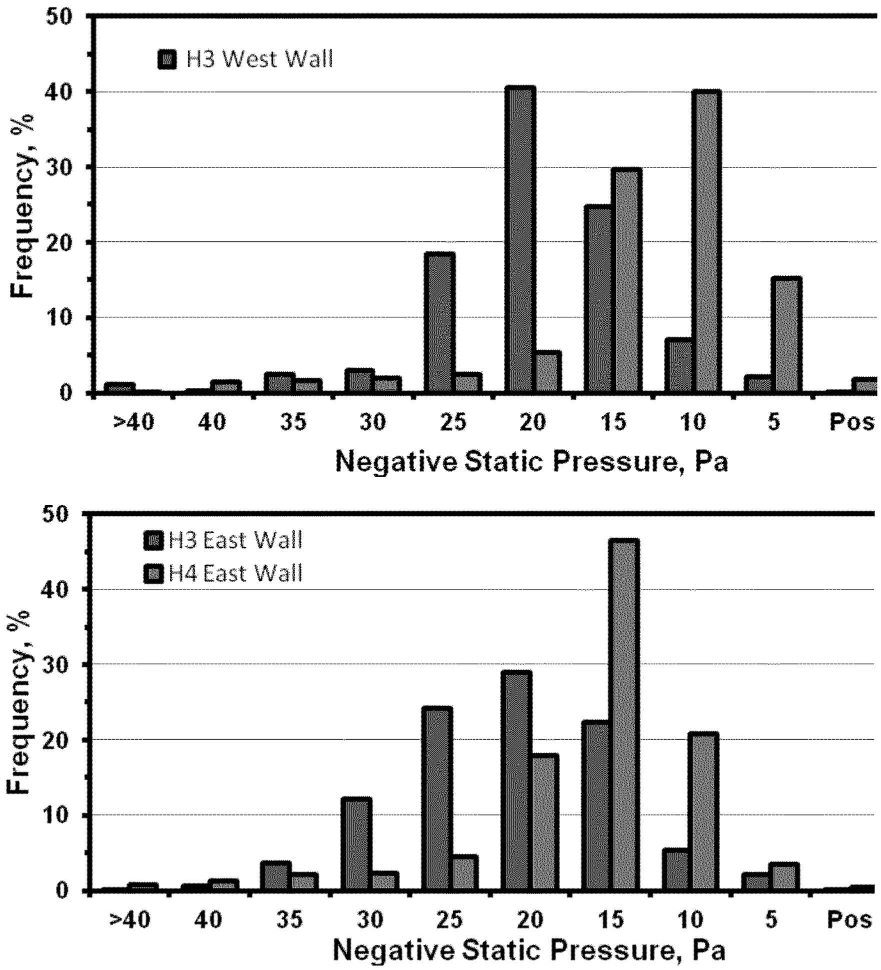


Figure 5.2. Distributions of static pressure in H3 and H4.

Table 5-5. Monthly mean±SD of airflow, temperature, and pressure at NC2B.

Variable	H3 airflow, m^3/h-hd	H4 airflow, m^3/h-hd	H3 Exh T, °C	H4 Exh T, °C	Inlet T, °C	H3 dP, Pa	H4 dP, Pa
Average Daily Means							
Valid days	607	612	712	712	709	711	712
Daily min	1	1	14	17	-6	-27	-30
Daily max	11	11	32	31	32	-9	-9
2-yr mean	4.33±3.62	4.22±3.52	24.7±2.9	25±2.6	17.2±8.4	-17.8±3.6	-16.9±2.8
1st yr mean	5.06±3.84	4.56±3.57	24.3±2.8	25±2.49	17.8±8.1	-18.5±2.9	-16.9±1.9
2nd yr mean	3.67±3.27	3.90±3.44	25.0±2.9	25.0±2.8	16.6±8.6	-17.1±4.0	-16.9±3.5
Average Hourly Means							
Valid hours	16185	16421	17263	17263	17216	17239	17249
Hourly min	0.40	0.42	8.56	10.4	-8.9	-42.7	-45.5
Hourly max	10.20	10.60	36.92	37.4	38.9	0.7	-1.4
2-yr mean	4.26±3.8	4.12±3.7	24.6±3.5	25±3.3	17.1±9.3	-17.8±4.6	-16.9±5.2
1st yr mean	4.75±3.9	4.38±3.7	24.3±3.7	25±3.3	17.7±9.1	-18.5±3.9	-17±3.7
2nd yr mean	3.81±3.6	3.87±3.7	25±3.3	25±3.3	16.5±9.5	-17.1±5.2	-16.9±6.4

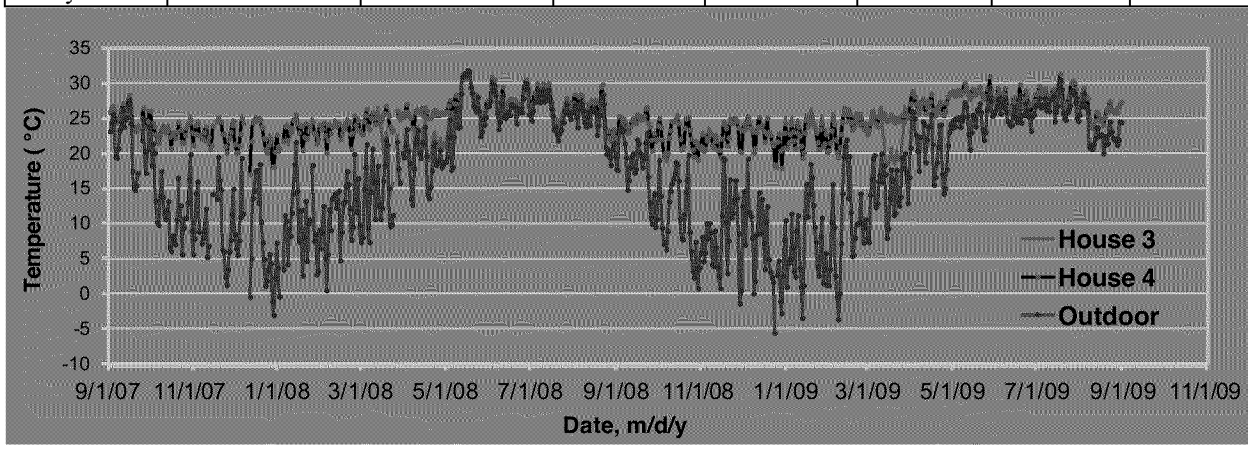


Figure 5.3. Indoor and ambient temperatures at NC2B.

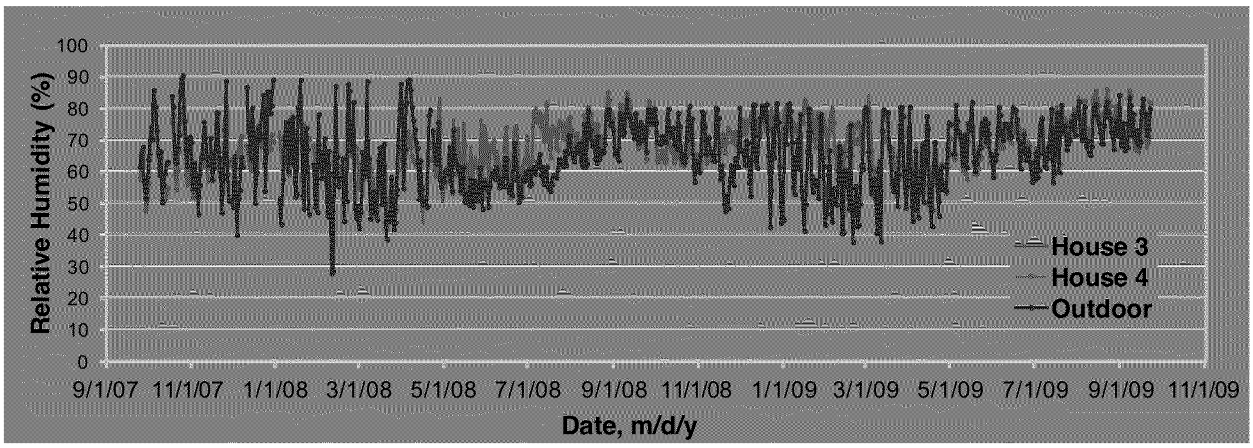


Figure 5.4. Indoor and ambient relative humidities at NC2B.

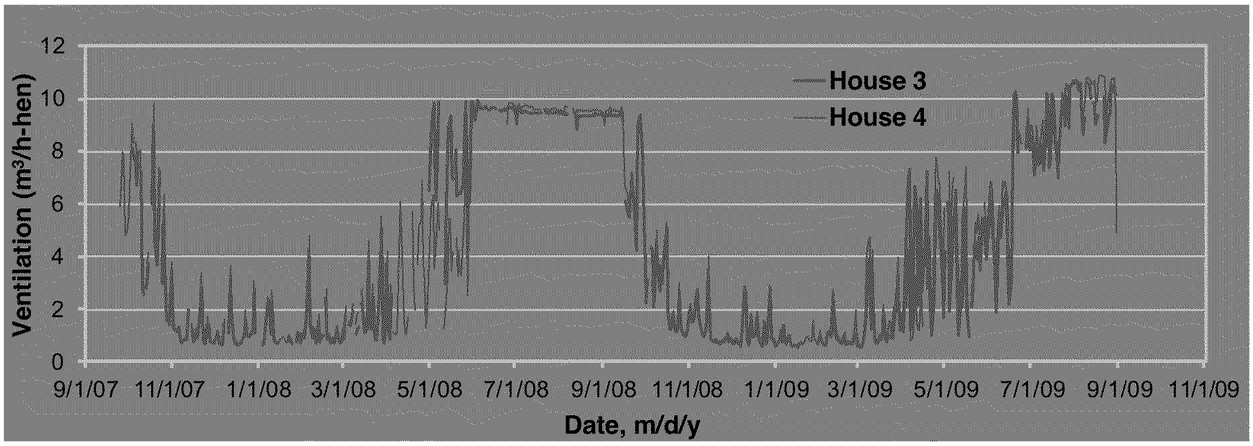


Figure 5.5. Hen specific ventilation rate at NC2B.

5.6.3. Ammonia Concentration and Emission

The DM NH_3 concentrations of all four air streams are plotted in Figure 5.6, and a summary of daily concentrations are given in Table 5.-66. The inlet concentration was generally at least an order of magnitude lower than¬ any¬ house's¬ exhaust¬ concentration,¬ meaning¬ that¬ th the NH_3 in the house exhaust was in fact generated in the house. The daily mean NH_3 concentrations averaged approximately 0.7±0.3 ppm in the inlet air, and 20.9±17.1 and 19.9±15.9 ppm in the H3 and H4 exhausts, respectively.

Table 5-6. Summary of daily mean ammonia concentrations.

Variable	Inlet, ppm	H3 Exhaust,ppm	H4 Exhaust,ppm
Average Daily Means			
Valid days	680	656	659
Daily min	0	1	1
Daily max	2	70	64
2-yr mean	0.7±0.3	20.9±17.1	19.9±15.9
1st yr mean	0.6±0.4	19.6±17.9	20±17.5
2nd yr mean	0.8±0.3	22.2±16.2	19.7±14
Average Hourly Means			
Valid hours	16407	16130	16117
Daily min	-0.5	-0.4	-0.4
Daily max	3.2	103.1	88.3
2-yr ADM	0.7±0.4	20.8±18.5	19.9±17.3
1st yr ADM	0.6±0.4	19.6±19	20±19
2nd yr ADM	0.8±0.3	22.2±17.9	19.7±15.4

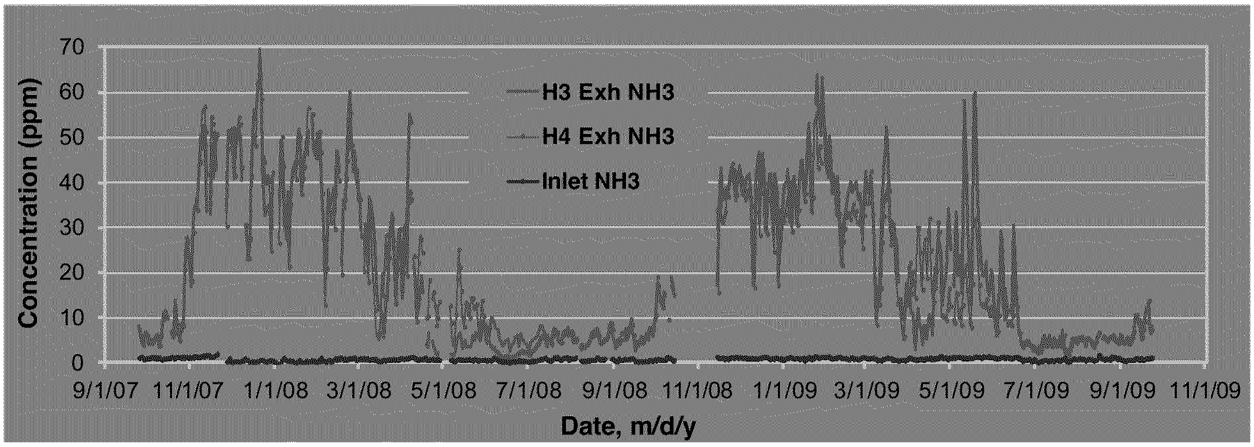


Figure 5.6. Daily means of ammonia concentrations.

Daily mean area and egg-specific NH_3 emissions are plotted in Figure 5.7 and Figure 5.8, respectively. Large spikes in the egg-specific NH_3 emissions (e.g., up to about 900 g/doz in the first week of May, 2009) occurred when the house had just been re-stocked (thus egg production was very low), but a significant amount of manure remained from the previous flock. The ADM house-, hen-, mass- and area-specific NH_3 emission rates from H3 and H4 are also shown in Table 5.-77. The area-specific daily NH_3 emissions averaged 18.0±7.0 and 17.2±5.7 g $d^{-1}m^{-2}$ for H3 and H4, respectively.

The daily mean LM-specific NH_3 emissions averaged 195±71and 201±62 g·$d^{-1}AU^{-1}$ for H3 and H4, respectively (Table 5.-77). The daily mean LM-specific NH_3 emissions from the houses agreed very well throughout the study. These emission rates were less than reported in studies in Iowa and Pennsylvania (Liang et al., 2005) where the LM-specific emission rates from high-rise layer houses were between 257 and 323 g/d-AU. Fabbri et al. (2007) reported an annual average NH_3 emission rate of 144 g/d-AU from a high-rise layer house in Europe. The differences observed in the literature were most likely caused by seasonal sampling periods and weather during which emissions were measured.

The averages of hourly and daily means were very similar between H3 and H4, even though more data was included with the hourly means because of the 75% completion rule applied to daily means. For example with the house-specific rates in H3, 15,393 h were valid over the same period during which 622 d were valid. Only 3% more data becomes available by using hourly means and this assumes that each of the valid days were 100% complete.

Figure 5.9 illustrates the pattern of emissions in relation to time of day in H3 and H4. The emission rates were slightly elevated at midday in both houses, and were likely related to changes in animal activity, temperature and/or airflow.

Table 5-7. Average NH_3 emission rates derived from daily and hourly mean data.

Variable	House 3	House 4
NH_3 emission rates from daily means		
House-specific, kg d^{-1}	55.4±21.2 (622)	54.3±18.0 (633)
Area-specific, g $d^{-1}m^{-2}$	18.0±7.0 (622)	17.2±5.7 (633)
Hen-specific, g $d^{-1}hd^{-1}$	0.590±0.214 (603)	0.590±0.184 (612)
LM-specific, g $d^{-1}AU^{-1}$	195±71 (603)	201±62(612)
Egg-specific, g doz^{-1}	13.2±43.1 (618)	12.1±28.2(627)
NH_3 emission rates from hourly means		
House-specific, kg d^{-1}	55.3±25.7 (15,393)	54.5±23.2 (15,613)
Area-specific, g $d^{-1}m^{-2}$	17.6±8.2 (15,393)	17.3±7.4 (15,613)
Hen-specific, g $d^{-1}hd^{-1}$	0.590±0.263 (14,882)	0.592±0.243 (15,109)
LM-specific, g $d^{-1}AU^{-1}$	194±87 (14,882)	202±83 (15,109)

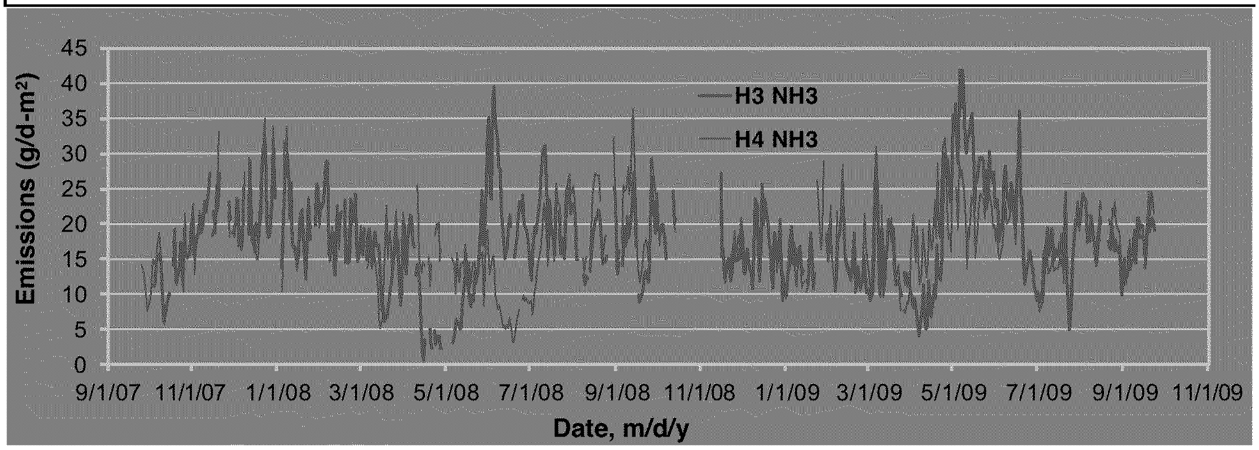


Figure 5.7. Daily means of area-specific ammonia emissions.

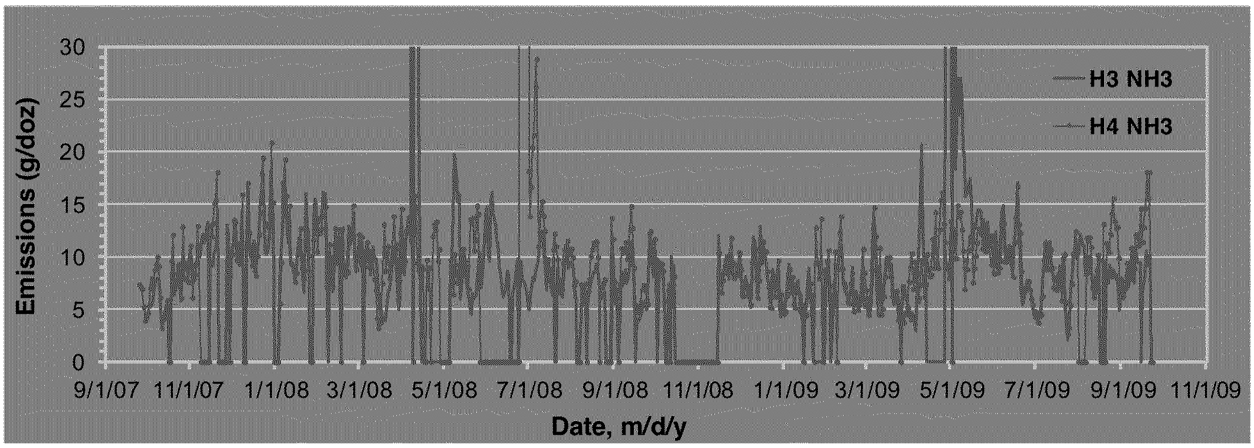


Figure 5.8. Daily mean egg-specific NH_3 emissions.

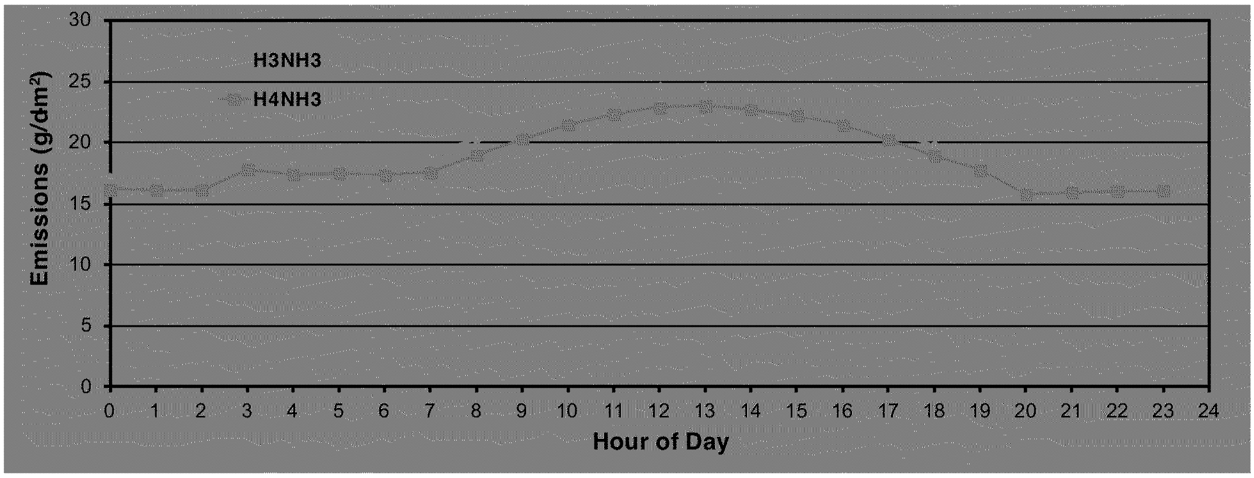


Figure 5.9. Average ammonia emission by hour of day.

Single variable regression between NH_3 emission averages and key factors (Table 5.-88) were conducted to determine which factors account for the most variation in emissions by themselves regardless of whether the factor was a direct effect. The H3 NH_3 emission rate was positively correlated with inlet (ambient) and exhaust temperatures as shown in Figure 5.10 for exhaust temperature of H3. In general the factors associated with inlet temperature (e.g. exhaust temperature, solar radiation, ventilation rate, exhaust RH, atmospheric pressure) were the most influential followed by flock characteristics (hen activity, hen age, water consumption).

Table 5-8. Correlation between area-specific NH_3 emission and various factors (* = p>0.05).

Parameter	Averaging interval	r
Inlet (ambient) temperature	Hourly	0.280
Exhaust temperature	Hourly	0.275
Solar radiation	Hourly	0.206
Ventilation rate	Hourly	0.205
Wind speed	Hourly	0.196
Hen activity	Hourly	0.177
Static pressure	Hourly	0.127
Water consumption	Daily	0.112
Live mass density	Daily	0.041*
Inlet relative humidity	Hourly	0.012
Time of day	Hourly	-0.003*
Feed intake	Daily	-0.059*
Exhaust relative humidity	Hourly	-0.243
Atmospheric pressure	Hourly	-0.031
Hen age	Daily	-0.099
Manure accumulation	Daily	-0.141

A stepwise multi-variable regression including two-way interactions was conducted to gain greater understanding about factors affecting area-specific emissions from full and active houses (Table 5.-9). It appeared that hen characteristics coupled with temperature related factors had the greatest influences. Surprisingly, hen age appeared as the dominant factor in the analysis of both hourly and daily means. Choosing exhaust temperature and live mass density to represent environment and hen factors, empirical NH_3 emission prediction equations 5.1 and 5.2 were developed for each house. However, based on the fact that hen age accounted for a significant amount of the variation as shown in Table 5.9, hen age could be considered as an additional independent variable since it is independent of exhaust temperature and the number of hens in the building (live mass density).

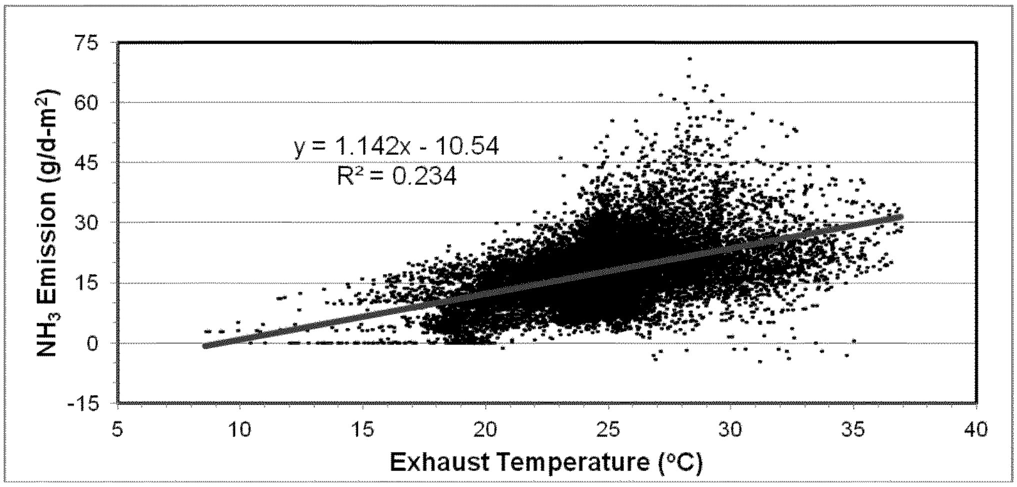


Figure 5.10. Influence of exhaust temperature on H3 area-specific NH3 emission rate.

The empirical regressions based on live mass density and exhaust temperature for hourly, daily and weekly means are given in Figures 5.1 and 5.2.

Hourly: $E = -22.159 + 0.386\,D + 0.912\,T$, $R^2 = 0.159$ (5.1)
Daily: $E = -1.964 + 0.176\,D + 0.498\,T$, $R^2 = 0.045$ (5.2a)
Weekly: $E = -9.57 + 0.392\,D + 0.522\,T - 0.0055A$, $R^2 = 0.067$ (5.2b)

Where E = NH_3 emission, g/d-m^2, D = live mass density, kg/m^2, T = exhaust temperature, °C, and A = hen age since hatch, d

5.6.4. Hydrogen Sulfide Concentration and Emission

The DM exhaust concentrations (Figure 5.11) showed very good agreement between houses (Table 5.-1010). The daily H_2S concentrations ranged from -1 to 31 ppb for H3 and H4. Slight negative concentrations are expected because of the way that concentrations were corrected coupled with very low concentrations at times. The average daily mean H_2S concentrations were 0.9±1.4 ppb for inlet, 9.2±5.8 ppb for H3 exhaust and 9.6±5.1 ppb for H4 exhaust.

The ADM LM-specific H_2S emissions were 193±129 and 214±143 mg $d^{-1}AU^{-1}$ for H3 and H4, respectively (Table 5.-1111). The DM area-specific H_2S emissions averaged 17.6±11.6 mg d^{-1} m^{-2} and 19.1±12.7 mg $d^{-1}m^{-2}$ for houses H3 and H4 (Figure 5.12), which was about 50% less than the daily mean emissions of 30 to 35 mg $m^{-2}d^{-1}$ reported by Gay et al. (2005). The H_2S emissions from H3 and H4 showed high variation with time of day (Figure 5.12) and two daily peaks, at approximately 5 am and 7 pm.

Table 5-9. Parameters influencing area-specific NH_3 emission, listed by significance.

Combined Hourly Means		Combined Daily Means	
Parameter	**R^2**	**Parameter**	**R^2**
Solar * Hen Age	0.215	Feed * Ventilation	0.142
Hen Activity * Hen Age	0.228	Hen Age	0.166
Exhaust Temp * Hen Age	0.249	Hen Age * Exhaust Temp	0.190
Hen Activity * LMD	0.266	Hen Age * Ventilation	0.245
House	0.274	Hen Age * Manure Age	0.255
Hen Activity	0.282	Manure Age	0.286
Exhaust Temp * Exhaust RH	0.289	LMD * Manure Age	0.291
Solar * Hen Activity	0.292	Manure Age * Exhaust Temp	0.309
Hen Age	0.297	Manure Age * Inlet Temp	0.323
LMD * Hen Age	0.314	Hen Age * Inlet Temp	0.342
Exhaust Temp	0.323	Ventilation * Inlet Temp	0.379
Exhaust Temp * Solar	0.334	Ventilation * Exhaust Temp	0.411
Inlet RH * Solar	0.337	House	0.417
Ventilation * Inlet RH	0.340	Water * Hen Age	0.429
Ventilation	0.352	Feed * Hen Age	0.435
Ventilation * LMD	0.357	LMD * Inlet Temp	0.436
Exhaust RH * Hen Age	0.366	Inlet Temp	0.437
LMD	0.369	LMD * Water	0.439
Ventilation * Exhaust Temp	0.384	Water	0.445
Ventilation * Hen Activity	0.395	Water * Inlet Temp	0.447
Ventilation * Hen Age	0.397	Water * Manure Age	0.452
Exhaust RH	0.398	Water * Ventilation	0.458
Exhaust RH * Hen Activity	0.401	Feed * Manure Age	0.464
Inlet RH * Hen Activity	0.402	Feed * Exhaust Temp	0.466
Inlet RH	0.403	Ventilation	0.469
Exhaust RH * Solar	0.405	Feed * Water	0.470
Solar	0.406	LMD * Exhaust Temp	0.472
Ventilation * Solar	0.406	Exhaust Temp	0.482
Exhaust Temp * Hen Activity	0.409	LMD * Ventilation	0.485
Exhaust RH * LMD	0.410		
Inlet RH * LMD	0.410		
Solar * LMD	0.412		
Inlet RH * Hen Age	0.412		
Ventilation * Exhaust RH	0.415		

Table 5-10. Summary of daily mean hydrogen sulfide concentrations.

Variable	Inlet, ppb	H3 Exhaust, ppb	H4 Exhaust, ppb
Average Daily Means			
Valid days	679	655	663
Daily min	0	-1	1
Daily max	16	31	26
2-yr ADM	0.9±1.4	9.2±5.8	9.6±5.1
st yr ADM	0.9±1.6	7±4.3	8.1±4.2
2nd yr ADM	0.9±1.3	11±6.3	10.8±5.4
Average Hourly Means			
Valid hours	16392	16147	16248
Daily min	-2.0	-2.0	-4.0
Daily max	46.8	114	55.1
2-yr ADM	0.9±2.2	9.2±6.7	9.6±6.2
1st yr ADM	0.9±2.3	7.1±5.0	8.1±5.4
2nd yr ADM	0.9±2.1	11±7.5	10.8±6.6

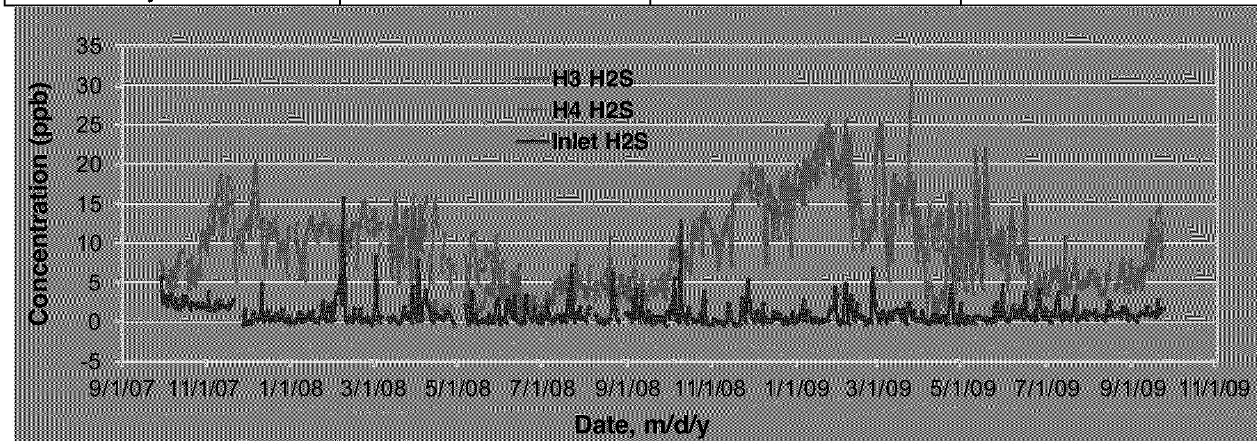


Figure 5.11. Daily means of hydrogen sulfide concentrations.

Table 5-11. Average daily H_2S emission rates derived from daily and hourly mean data.

Variable	House 3	House 4
H_2S emission rates from daily means		
House-specific, g d^{-1}	55.51±36.5 (627)	60.2±39.8 (634)
Area-specific, mg $d^{-1}m^{-2}$	17.6±11.6 (627)	19.1±12.7 (634)
Hen-specific, mg $d^{-1}hd^{-1}$	0.58±0.38 (627)	0.64±0.40 (614)
LM-specific, mg $d^{-1}AU^{-1}$	193±129 (627)	214±143 (634)
Egg-specific, mg doz^{-1}	13.3±42.2 (610)	18.2±96.1(579)
H_2S emission rates from hourly means		
House-specific, g d^{-1}	55.2±55.9 (15530)	60.3±65.8 (15,642)
Area-specific, mg $d^{-1}m^{-2}$	17.5±17.7 (15530)	19.2±20.9 (15,642)
Hen-specific, mg $d^{-1}hd^{-1}$	0.57±0.58 (15530)	0.625±0.642 (15,642)
LM-specific, mg $d^{-1}AU^{-1}$	214±224 (15530)	119.5±196.8 (15,642)

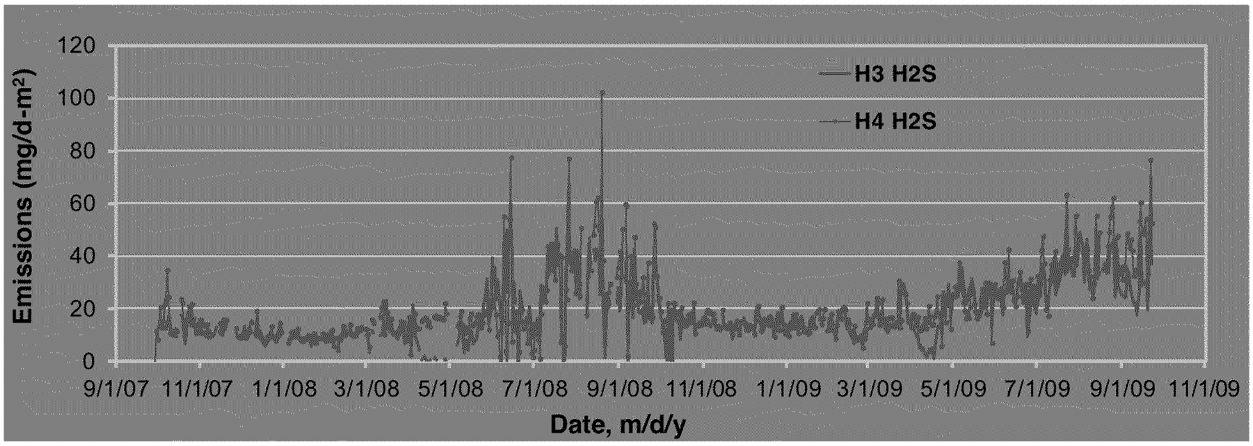


Figure 5.12. Daily means of area-specific hydrogen sulfide emissions.

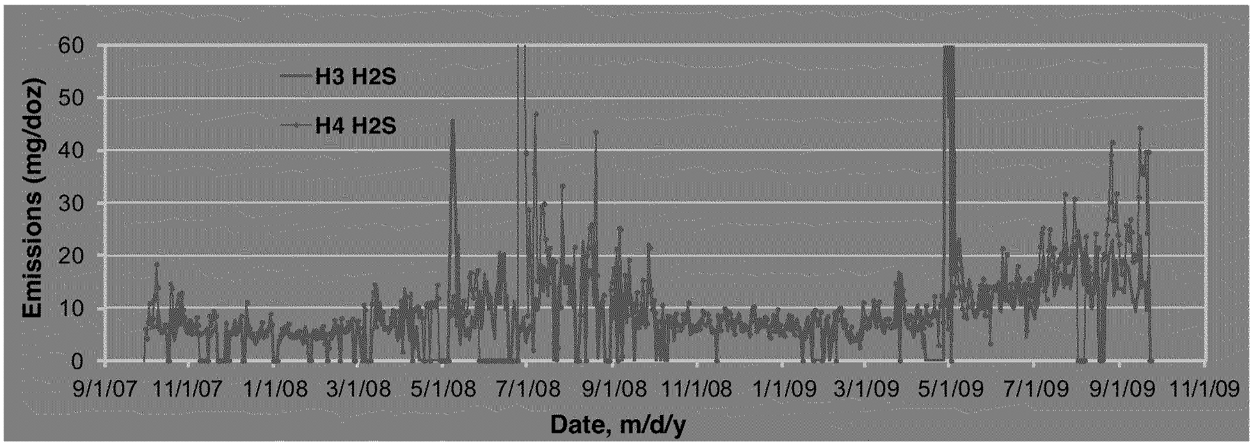


Figure 5.13. Daily means of egg-specific H_2S emission.

Single variable regression was performed between hourly H_2S emission averages and key factors Table 5.-1212. In both houses, H_2S emission was positively influenced by airflow rate, exhaust temperature and ambient temperatures (r>0.3). These variables are interdependent thus only one of the variables should be used in a prediction equation (discussed later).

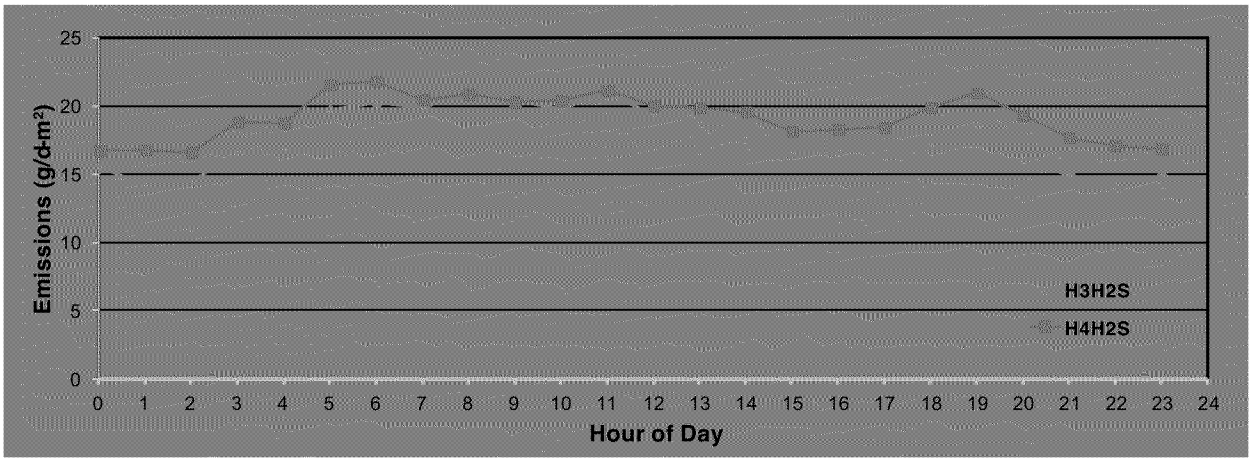


Figure 5.14. Average hydrogen sulfide emission by hour of day.

Table 5-12. Correlations between area-specific H_2S emission and various factors (*=p>0.05).

Parameter	Averaging interval	r
Ventilation rate	Hourly	0.403
Exhaust temperature	Hourly	0.279
Inlet temperature	Hourly	0.266
Feed	Daily	0.253
Water	Daily	0.201
Exhaust RH	Hourly	0.193
Static Pressure	Hourly	0.158
Inlet RH	Hourly	0.100
Solar radiation	Hourly	0.043
Hen activity	Hourly	0.023
Time of day	Hourly	0.001*
Wind speed	Hourly	-0.051
Live Mass Density	Daily	-0.117
Atmosphere pressure	Hourly	-0.156
Manure Age	Daily	-0.337
Hen Age	Daily	-0.510

A statistical analysis was conducted to discover which variables or interactions of variables significantly influenced H_2S emissions (Table 5.-1313). Top flock factors were hen age, live mass density, and feed and water consumption. Top thermal factors were ventilation rate and exhaust temperature.

Table 5-13. Parameters influencing area-specific H_3S emission, listed by significance.

Combined Hourly Means		Combined Daily Means	
Parameter	**R^2**	**Parameter**	**R^2**
Ventilation * Wind Speed	0.188	Feed * Ventilation	0.380
House	0.205	Hen Age * Ventilation	0.398
Live Mass Density	0.218	Manure Age * Ventilation	0.411
Ventilation * Exhaust Temp	0.225	Water * Exhaust Temp	0.421
Exhaust Temp	0.227	House	0.425
Atmospheric pressure	0.229	Live Mass Density	0.428
Ventilation * Atmospheric pressure	0.229	Hen Age * Manure Age	0.428
Ventilation	0.230	Live Mass Density * Manure Age	0.435
Atmospheric Pressure * Live Mass Density	0.230	Feed * Hen Age	0.442
Exhaust Temp * Live Mass Density	0.230	Manure Age	0.446
Exhaust Temp * Wind Speed	0.231	Ventilation * Exhaust Temp	0.450
Atmospheric Pressure * Wind Speed	0.234	Hen Age * Exhaust Temp	0.452
Inlet RH * Wind Speed	0.235	Ventilation * Inlet Temp	0.453
Inlet RH	0.235		
Inlet RH * Atmospheric pressure	0.235		
Ventilation * Inlet RH	0.235		
Wind Speed	0.235		

Choosing live mass density and exhaust temperature to represent environment and flock factors, the empirical H_2S emission prediction equations 5.3 and 5.4 were developed for each house.

Hourly: $E = -2.314 - 0.397\ D + 1.600\ T$, $R^2 = 0.08$ (5.3)
Daily: $E = -29.6 - 0.248\ D + 2.43\ T$, $R^2 = 0.27$ (5.4)

Where E = H_2S emission, g/d-m^2, D = live mass density, kg/m^2, and T = exhaust temperature, °C.

The model for predicting daily emissions did a better job of accounting for the variance in the data (R^2 of 27% vs. 8%).

5.6.5. Carbon Dioxide Concentration and Emission

Daily mean CO_2 concentrations calculated from daily data (Figure 5.15, Table 5.1414) ranged from 268 to 1105 ppm in the inlet air (n=657 d), 528 to 3910 ppm in H3 exhaust (n=633 d), and 540 to 3786 ppm in H4 exhaust (n=641 d). The mean concentrations for all three air streams were 561±163 ppm (inlet), 1721±978 ppm (H3), 1742±920 ppm (H4). The average inlet concentration was thus slightly higher than the current global atmospheric CO_2 concentration of 392 ppm (http://co2now.org/), indicating some influence of house exhaust reentry on inlet concentration.

Table 5.14. Summary of daily mean carbon dioxide concentrations.

Variable	Inlet, ppm	H3 exhaust, ppm	H4 exhaust, ppm
Average Daily Means			
Valid days	657	633	641
Daily min	268	528	540
Daily max	1105	3910	3786
2-yr ADM	561±163	1721±978	1742±920
1st yr ADM	621±214	1689±964	1767±897
2nd yr ADM	503±30	1751±991	1719±942
Average Hourly Means			
Valid hours	15858	15582	15682
Daily min	248	380	475
Daily max	1284	4576	4429
2-yr ADM	562±166	1717±1050	1739±1003
1st yr ADM	622±217	1687±1038	1768±990
2nd yr ADM	503±38	1746±1060	1712±1016

The exhaust CO_2 concentrations were similar among houses (Table 5.-1515). As expected, the patterns of CO_2 concentrations (Figure 5.15) were similar to NH_3. Figure 5.16 shows the emission rates normalized to hens and floor area. The ADM CO_2 emissions for H3 and H4 were 23.9±3.5 and 28.1±4.0 kg d^{-1}AU^{-1}, respectively (or 72.5±11.5 and 82.2±12.1 g d^{-1}hd^{-1}).

The area-specific daily CO_2 emissions averaged 2.15±0.48 kg d^{-1} m^{-2} for H3 and 2.4±0.5 kg d^{-1} m^{-2} for H4 (Table 5.-1515).

The pattern of emissions in relation to time of day in H3 and H4 was similar to NH_3 (Figure 5.17). The emission rate was slightly elevated in both houses during midday, likely related to animal activity.

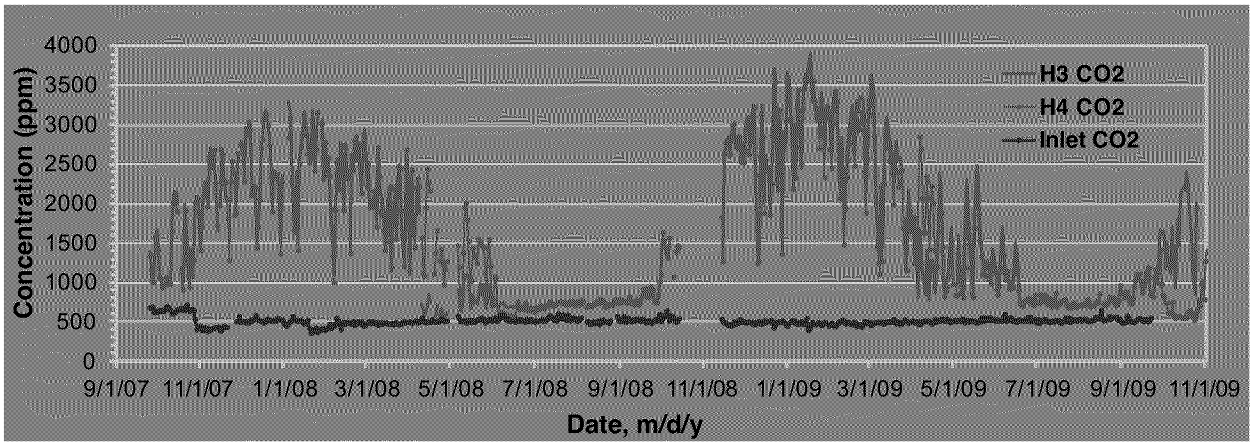


Figure 5.15. Daily means of carbon dioxide concentration.

Table 5-15. Average daily CO_2 emission rates derived from daily and hourly mean data.

Variable	House 3	House 4
CO_2 emission rates from daily means		
House-specific, kg d^{-1}	6761±1516 (601)	7545±1447 (613)
Area-specific, kg $d^{-1}m^{-2}$	2.15±0.48 (601)	2.4±0.5 (613)
Hen-specific, g $d^{-1}hd^{-1}$	72.5±11.46 (583)	82.2±12.08 (593)
LM-specific, kg $d^{-1}AU^{-1}$	23.9±3.50 (583)	28.1±4.0(593)
Egg-specific, g doz^{-1}	2100±7800 (588)	2150±6060(597)
CO_2 emission rates from hourly means		
House-specific, kg d^{-1}	6742±1914 (14,866)	7560±1927 (15,097)
Area specific, kg $d^{-1}m^{-2}$	2.14±0.61 (14,866)	2.40±0.61 (15,097)
Hen-specific, g $d^{-1}hd^{-1}$	70.1±20.7 (14,866)	79.7±22.9 (15,097)
LM-specific, kg $d^{-1}AU^{-1}$	23.1±6.71 (14,866)	27.3±7.80 (15,097)

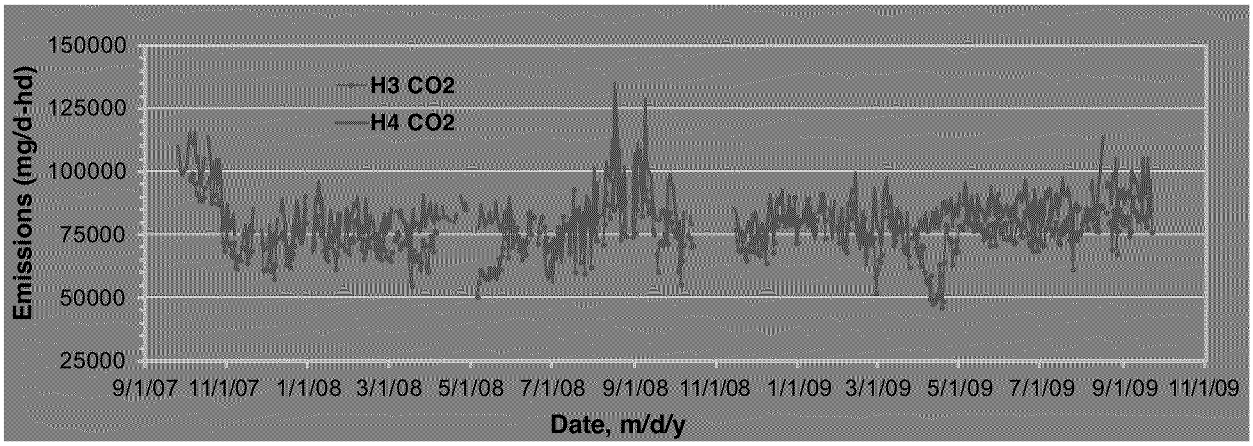
According to the single-factor correlations, CO2 emissions were mostly influenced by ventilation rate, feed intake, inlet temperature, exhaust temperature, hen age, and LMD (Table 5.-1616). The multi-factor analysis of variance showed high influence of flock characteristics such as live mass density and feed consumption (Table 5-17). Hen activity, age and LMD affected hourly mean emissions while feed consumption, ventilation rate, and LMD influenced daily means the most. Based on temperature and LMD, the empirical CO_2 emission prediction equations are as follows:

Hourly: $E = 2587 + 25.78\ T - 18.52\ D$, $R^2 = 0.08$ (5.5)

Daily: $E = -2444 + 91.46\ D + 38.11\ T$, $R^2 = 0.09$ (5.6)

Where E = CO_2 emission, g/d-m^2, D = live mass density, kg/m^2, and T = exhaust temperature, °C.

The models account for only a small amount of the variance as indicated by low R^2 (<10%).



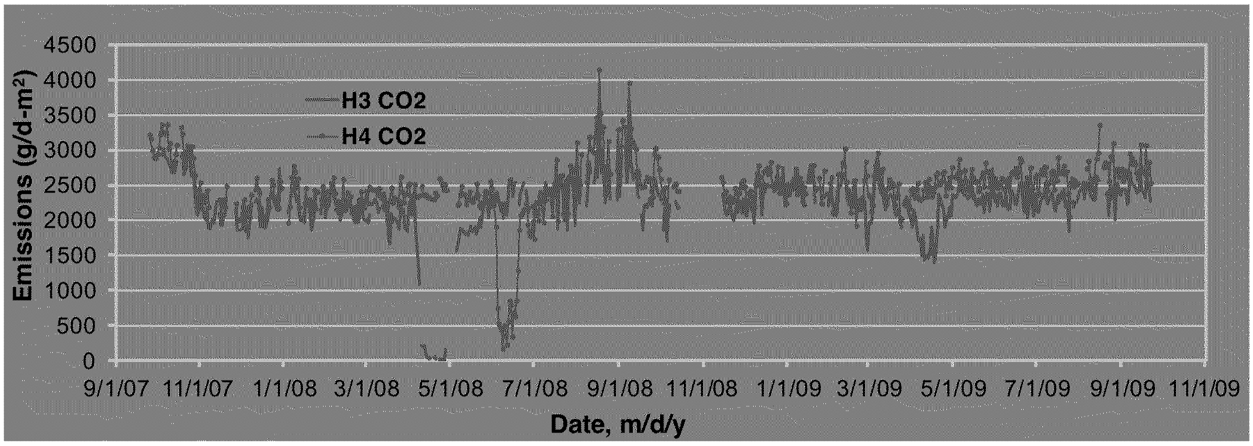


Figure 5.16. Daily means of carbon dioxide emission rate normalized two ways.

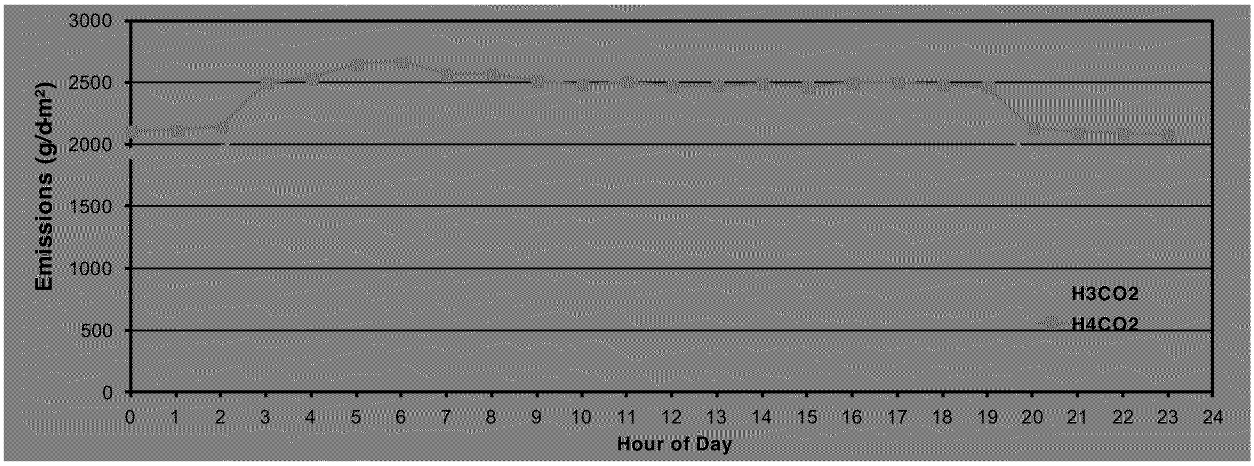


Figure 5.17. Average carbon dioxide emission by hour of day.

Table 5-16. Correlation coefficients (r) between area-specific CO_2 emission and various influencing parameters (* = p>0.05).

Parameter	Averaging interval	r
Ventilation rate	Hourly	0.333
Feed intake	Daily	0.316
Inlet temperature	Hourly	0.242
Hen activity	Hourly	0.222
Exhaust temperature	Hourly	0.205
Solar radiation	Hourly	0.180
Water consumption	Daily	0.124
Static Pressure	Hourly	0.106
Wind speed	Hourly	0.068
Exhaust RH	Hourly	0.012
Inlet RH	Hourly	-0.004*
Time of day	Hourly	-0.055
Atmosphere pressure	Hourly	-0.061
Manure Age	Daily	-0.0230*
Live mass density	Daily	-0.135
Hen Age	Daily	-0.139

Table 5-17. Parameters influencing area-specific CO_2 emission, listed by significance.

Combined Hourly Means		Combined Daily Means	
Parameter	**R^2**	**Parameter**	**R^2**
House	0.343	Manure Age * Ventilation	0.190
Hen Activity * Hen Age	0.436	Feed	0.294
Hen Activity * Live Mass Density	0.491	House	0.354
Solar * Wind Speed	0.496	Live Mass Density * Feed	0.426
Live Mass Density * Hen Age	0.501	Feed * Exhaust Temp	0.428
Solar * Hen Activity	0.516	Inlet Temp	0.442
Inlet Temp * Exhaust Temp	0.523	Feed * Manure Age	0.445
Exhaust Temp * Exhaust RH	0.530	Manure Age * Exhaust Temp	0.460
Inlet Temp * Solar	0.532	Live Mass Density * Inlet Temp	0.464
Exhaust RH * Live Mass Density	0.533	Live Mass Density * Ventilation	0.472
Inlet RH * Solar	0.534	Ventilation	0.482
Exhaust RH * Solar	0.537	Ventilation * Exhaust Temp	0.488
Hen Activity	0.539	Hen Age * Manure Age	0.495
Time of day * Inlet RH	0.545	Live Mass Density * Hen Age	0.499
Inlet Temp * Exhaust RH	0.546	Hen Age * Exhaust Temp	0.506
Time of day * Exhaust Temp	0.547	Hen Age * Inlet Temp	0.514
Wind Speed * Hen Age	0.548	Live Mass Density * Exhaust Temp	0.521
Exhaust Temp * Wind Speed	0.549	Exhaust Temp	0.524
Exhaust RH * Wind Speed	0.550	Water * Inlet Temp	0.528
Inlet Temp * Wind Speed	0.551	Water * Hen Age	0.530
Inlet Temp * Hen Age	0.552	Hen Age * Ventilation	0.532
Exhaust Temp * Hen Age	0.552	Manure Age * Inlet Temp	0.533
Time of day	0.552	Hen Age	0.534
Exhaust RH	0.553		
Exhaust Temp	0.554		
Inlet Temp * Inlet RH	0.554		
Inlet RH	0.555		
Exhaust RH * Hen Age	0.555		
Time of day * Wind Speed	0.555		
Inlet RH * Hen Activity	0.555		
Exhaust RH * Hen Activity	0.556		
Exhaust Temp * Hen Activity	0.556		
Inlet Temp * Hen Activity	0.557		
Exhaust Temp * Live Mass Density	0.557		
Solar	0.557		
Inlet Temp	0.557		
Hen Age	0.557		
Wind Speed	0.558		
Live Mass Density	0.558		
Inlet Temp * Live Mass Density	0.559		

5.6.6. PM Concentration and Emission

5.6.6.1. PM10 Concentration and Emission

Inlet PM_{10} concentrations were generally much lower than the house exhaust concentrations Table 5.-2626. The daily mean PM concentrations measured at the primary representative exhaust fan generally agreed well among both houses.

The exhaust PM_{10} concentrations reached their minimal values during May to September when ventilation rate was highest (Figure 5.18). The ADM PM_{10} concentrations were 36±23 μg/m^3 for inlet air, and 490±342 μg/m^3 and 445±322 μg/m^3 for H3 and H4 exhaust air. The ADM concentrations were similar to average hourly mean PM_{10} concentrations, which were 35±41 μg/m^3 (13,233 h), 480±448 μg/m^3 (13,622 h), and 436±415 μg/m^3 (10169 h) at the inlet, and H3 and H4 exhausts, respectively.

Table 5-18. Summary of daily mean PM_{10} concentrations.

Variable	Inlet, μg/m^3	H3 Exhaust, μg/m^3	H4 Exhaust μg/m^3
Average Daily Means			
Valid days	527	553	413
Daily min	7	27	-141
Daily max	232	2340	1410
2-yr ADM	36±23	490±342	445±322
1st yr ADM	36±23	399±257	338±275
2nd yr ADM	36±24	569±385	619±318
Average Hourly Means			
Valid hours	13233	10169	13622
Daily min	-17	-373	-129
Daily max	1001	2617	5053
2-yr ADM	35±41	436±415	480±449
1st yr ADM	36±43	330±340	391±340
2nd yr ADM	35±39	613±466	559±513

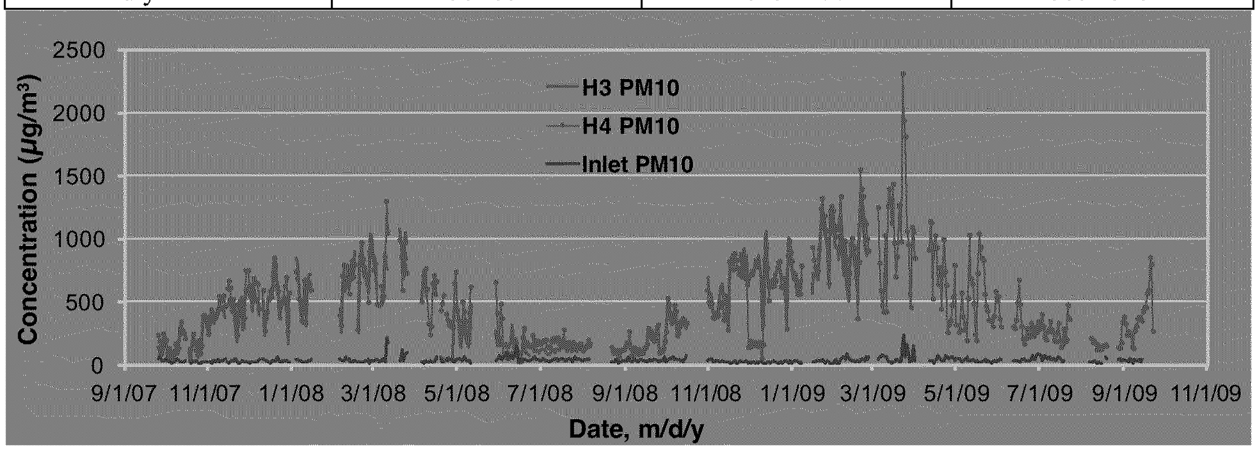


Figure 5.18. Daily means of PM_{10} concentrations.

The overall mean (±SD) PM_{10} house-specific, hen-specific and area-specific (Table 5.-1919, Figure 5.19) emissions are presented below. The average daily means LM-specific PM10 emissions were 5.10±2.49 and 8.25±4.14 g d^{-1}AU^{-1} for H3 and H4, respectively. These PM_{10}

emission rates agreed well with PM_{10} emissions from a mechanical ventilated high-rise layer house in Iowa (Li et al. 2009), which averaged 7.45 g $d^{-1}AU^{-1}$. Like the Iowa study, the average daily mean LM-specific PM_{10} emission rates of this study were lower than the 16 g $d^{-1}AU^{-1}$ measured in Europe (Fabbri et al., 2007).

The area-specific daily PM_{10} emissions averaged 472±224 mg d^{-1} m^{-2} for H3 and 701±362 mg $d^{-1}m^{-2}$ for H4 (Table 5.-1919). The PM_{10} emission rates were also generally greater in warmer weather, which was mostly caused by higher ventilation rates and dryer materials. The hen-specific average daily mean PM_{10} emissions were 15.4±7.0 and 23.9±11.8 mg d^{-1} hd^{-1} for H3 and H4, respectively.

The PM_{10} emission peaked in accordance with the feeding schedule, likely because of increased animal activity and feed PM (Figure 5.20).

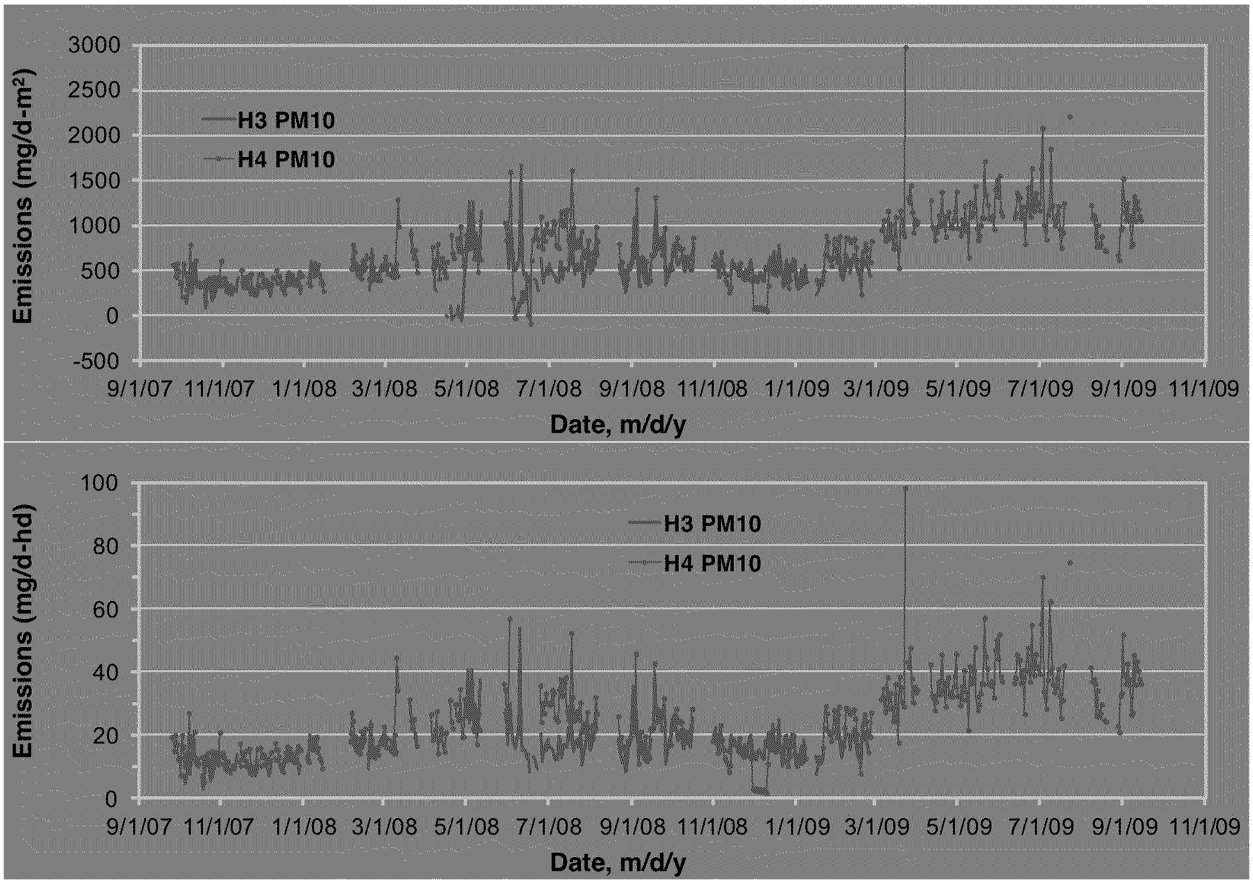


Figure 5.19. Daily means of PM10 emissions.

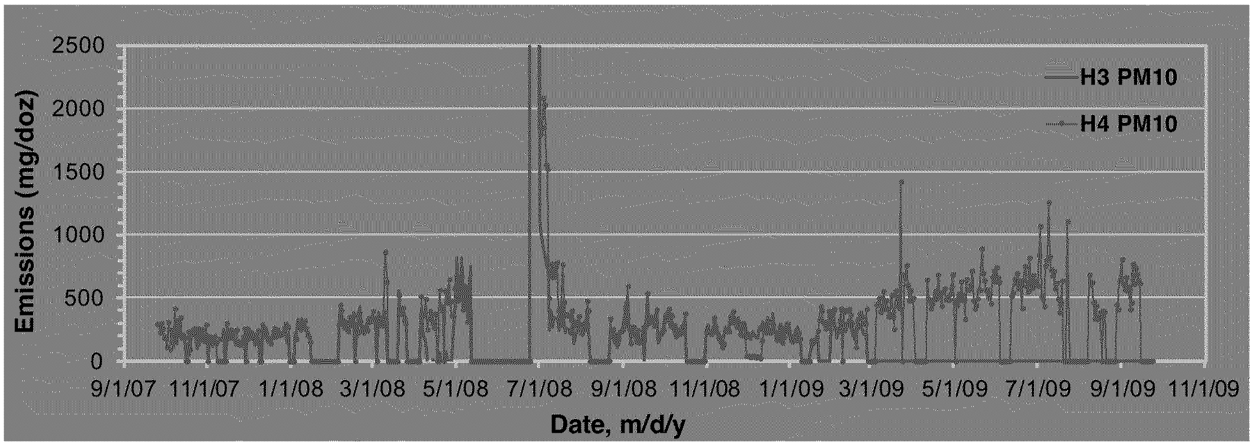


Figure 5.20. Daily means of egg-specific PM_{10} emission rate.

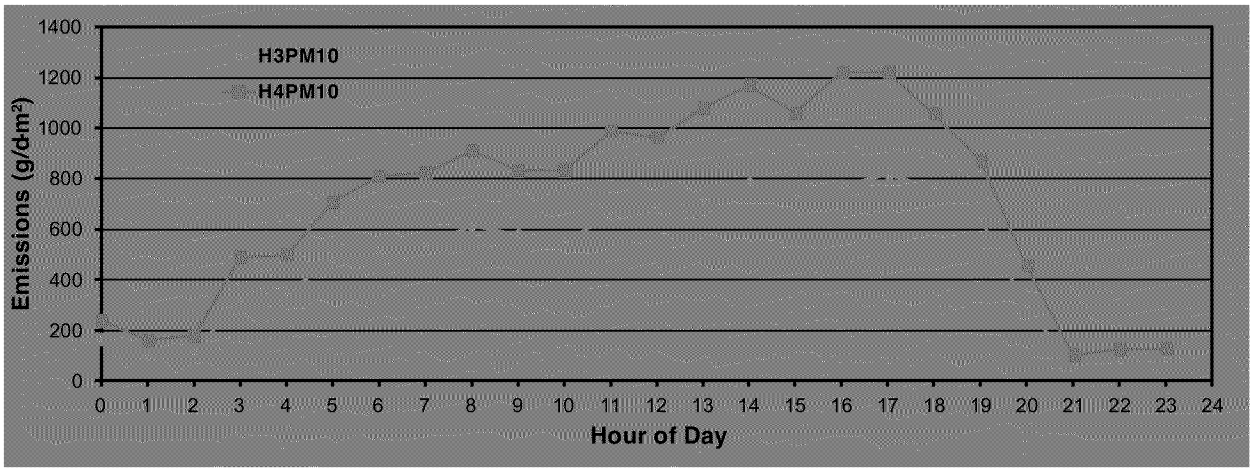


Figure 5.21. Average area-specific PM10 emission by hour of day.

Table 5-19. Average daily PM_{10} emission rates derived from daily and hourly mean data.

Variable	House 3	House 4
PM10 emission rates from daily means		
House-specific, g d^{-1}	1485±706 (381)	2207±1140(521)
Area-specific, mg $d^{-1}m^{-2}$	472±224 (381)	701±362 (521)
Hen-specific, mg $d^{-1}hd^{-1}$	15.40±7.01 (381)	23.90±11.75 (501)
LM-specific, g $d^{-1}AU^{-1}$	5.10±2.49 (381)	8.25±4.14(501)
Egg-specific, mg doz^{-1}	354±625 (350)	593±1646(493)
PM10 emission rates from hourly means		
House-specific, g d^{-1}	1493±1375 (9440)	2207±2229 (12,923)
Area-specific, mg $d^{-1}m^{-2}$	474±437 (9440)	701±708 (12,923)
Hen-specific, mg $d^{-1}hd^{-1}$	15.44±13.95 (9440)	23.02±23.62 (12,923)
LM-specific, g $d^{-1}AU^{-1}$	5.12±4.79 (9440)	7.94±8.16 (12,923)

More PM_{10} emissions occurred during warm weather and daytime as reflected by inlet and exhaust temperatures, solar radiation, ventilation rate and hen activity having the greatest positive single factor correlation while emissions were inversely proportional to hen age, live mass density and manure age (Table 5.-2020). Live mass density and exhaust temperature and associated thermal variables had the greatest influence in a 2-way ANOVA (Table 5.-2121).

Warm temperatures are associated with high airflows which dry the litter and feathers in the cages which are then dispersed by hen activity.

Table 5-20. Correlation between area-specific PM_{10} emission and various influencing parameters (* = p>0.05).

Parameter	Averaging Interval	r
Inlet temperature	Hourly	0.369
Exhaust temperature	Hourly	0.354
Solar radiation	Hourly	0.308
Ventilation rate	Hourly	0.265
Wind speed	Hourly	0.172
Hen activity	Hourly	0.151
Static pressure	Hourly	0.129
Time of day	Hourly	0.076
Atmosphere pressure	Hourly	-0.104
Inlet relative humidity	Hourly	-0.258
Exhaust relative humidity	Hourly	-0.295
Feed intake	Daily	0.188
Water consumption	Daily	0.020*
Hen age	Daily	-0.125
Live mass density	Daily	-0.370
Manure age	Daily	-0.430

The empirical PM_{10} emission predictions are given in equations 5.7 and 5.8.

Hourly: $E = 568.8 - 33.82\ D + 64.1\ T,\ R^2 = 0.15$ (5.7)
Daily: $E = 1443 - 40.12\ D + 39.9\ T,\ R^2 = 0.24$ (5.8)

Where $E = PM_{10}$ emission, g/d-m^2, D = live mass density, kg/m^2, and T = exhaust temperature, °C.

Table 5-21. Parameters influencing area-specific PM_{10} emission, listed by significance.

Hourly		Daily	
Parameter	**R^2**	**Parameter**	**R^2**
Time of Day * Solar	0.159	Live Mass Density	0.370
Atmospheric Pressure * Live Mass Density	0.309	Ventilation * Exhaust Temp	0.418
Exhaust RH * Solar	0.345	Manure Age * Inlet Temp	0.421
Ventilation	0.378	Hen Age * Manure Age	0.430
House	0.411	Live Mass Density * Manure Age	0.492
Time of Day	0.422	House	0.549
Ventilation * Exhaust RH	0.427	Inlet Temp	0.567
Ventilation * Solar	0.431	Live Mass Density * Inlet Temp	0.575
Inlet Temp * Hen Age	0.436	Manure Age * Ventilation	0.580
Exhaust RH * Hen Age	0.440	Hen Age	0.584
Solar * Hen Age	0.444	Feed * Exhaust Temp	0.588
Live Mass Density * Hen Age	0.453	Feed * Hen Age	0.589
Hen Age	0.456		
Exhaust RH * Atmospheric Pressure	0.457		
Ventilation * Hen Age	0.460		
Inlet Temp * Exhaust RH	0.462		
Inlet Temp * Exhaust Temp	0.464		
Inlet Temp	0.469		
Exhaust Temp * Hen Age	0.473		
Solar	0.476		
Exhaust Temp * Exhaust RH	0.478		
Solar * Live Mass Density	0.483		
Inlet RH * Solar	0.484		
Exhaust RH	0.495		
Ventilation * Inlet RH	0.496		
Exhaust Temp * Inlet RH	0.497		
Time of Day * Atmospheric Pressure	0.498		
Exhaust Temp * Atmospheric Pressure	0.498		
Inlet RH * Exhaust RH	0.499		
Inlet RH	0.499		
Ventilation * Static Pressure	0.499		
Ventilation * Exhaust Temp	0.500		
Ventilation * Inlet Temp	0.504		
Atmospheric Pressure	0.505		
Live Mass Density	0.506		
Exhaust Temp	0.506		
Inlet Temp * Solar	0.507		
Ventilation * Live Mass Density	0.507		
Exhaust Temp * Solar	0.508		
Exhaust RH * Live Mass Density	0.508		
Inlet RH * Atmospheric Pressure	0.508		
Time of Day * Inlet RH	0.508		
Atmospheric Pressure * Static Pressure	0.508		
Static Pressure	0.509		
Time of Day * Static Pressure	0.509		
Exhaust Temp * Live Mass Density	0.509		

5.6.6.2. $PM_{2.5}$ Concentration and Emission

The basic statistics of ADM and AHM $PM_{2.5}$ concentrations in the inlet air and house exhausts are presented below (Figure 5.22, Table 5.-2222). The daily means of $PM_{2.5}$ concentrations averaged approximately 14±5 μg/m^3 in the inlet air, and 34.4±22.9 and 38.4±14.1 μg/m^3 in the exhausts of H3 and H4, respectively. Concentrations of $PM_{2.5}$ were generally much lower than PM_{10} concentrations measured immediately before and after the $PM_{2.5}$ monitoring periods. This indicates that $PM_{2.5}$ was a very minor component, accounting for perhaps 5 to 10% of the PM_{10}.

Table 5-22. Summary of daily and hourly mean $PM_{2.5}$ concentrations.

Variable	Inlet, μg/m^3	H3 exhaust, μg/m^3	H4 exhaust μg/m^3
Average Daily Means			
Valid days	33	21	33
Daily min	4	-16	0
Daily max	25	68	64
2-yr ADM	14±5	35.4±22.9	38.4±14.1
1st yr ADM	15.2±3.7	44.4±15.6	48.1±9.2
2nd yr ADM	12.8±5.8	6.6±18.6	29.3±11.7
Average Hourly Means			
Valid hours	868	540	857
Daily min	-11.0	-335	-358
Daily max	46.8	561	440
2-yr ADM	14.3±8.9	44.9±90.7	40.8±60.1
1st yr ADM	15.7±7.1	46.9±32	50.1±26.9
2nd yr ADM	13.1±10.1	39.5±169.4	32.4±77.8

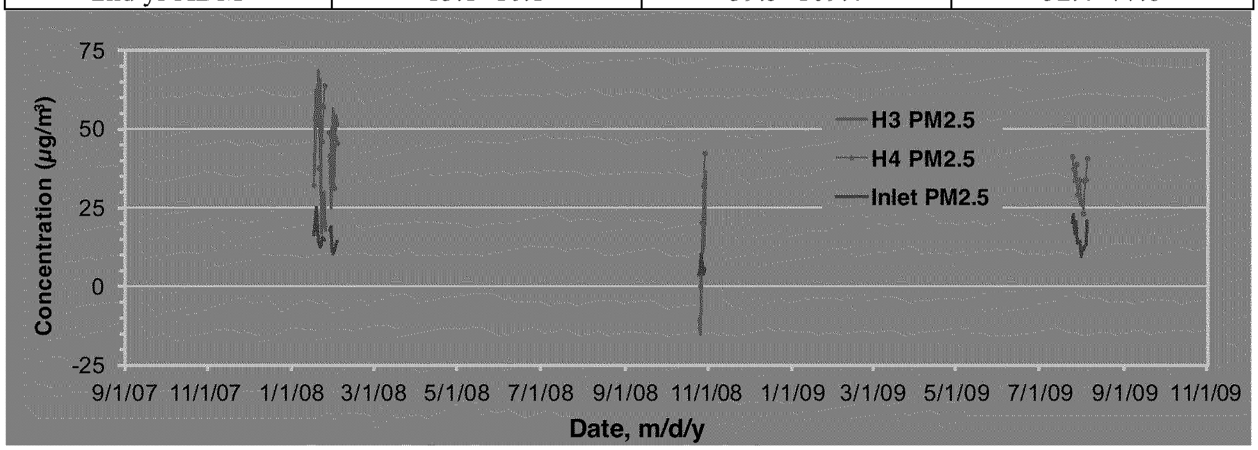


Figure 5.22. Daily means of $PM_{2.5}$ concentrations.

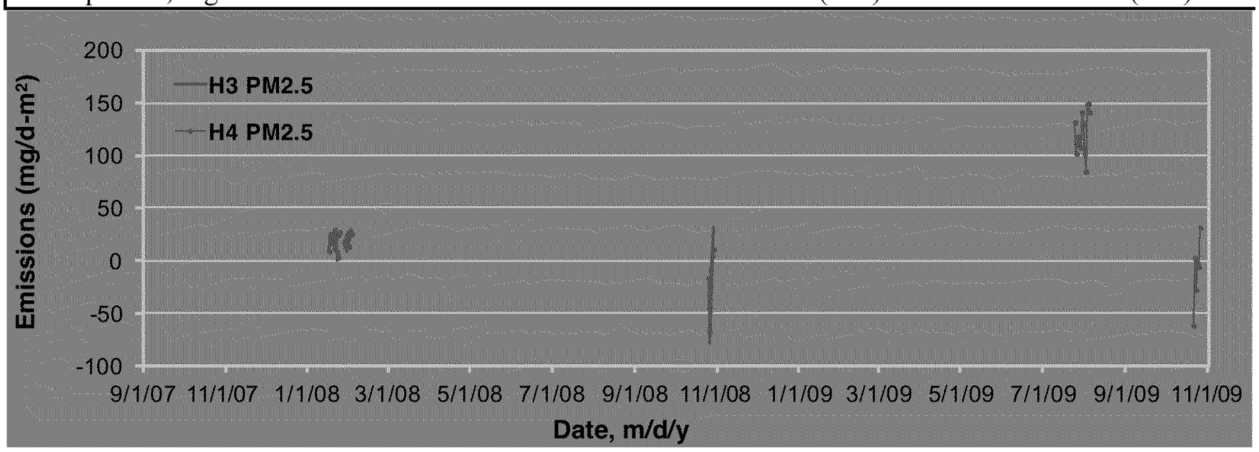
The overall mean (±SD) house-, hen-, area- and LM-specific $PM_{2.5}$ emissions are given in Figure 5.23 and Table 5.-2323. The ADM area-specific $PM_{2.5}$ emissions were 9.89±25.1 and 52.4±57.6 mg d^{-1} m^{-2} for H3 and H4, respectively . The ADM LM -specific PM $_{2.5}$ emission rates were 94.9±265 and 594±6512 mg d^{-1}AU^{-1} for H3 and H4 , respectively. The high v ariance in these means were highly variable because of the relatively low exhaust concentrations. Most of the $PM_{2.5}$ emissions from H3 were actually calculated to be negative, which meant that the measurements were obviously so low that they were less than the minimum quantitation limit of the emission measurement system. The average daily LM-specific $PM_{2.5}$ emissions were about an or der of magnitude lower than previous studies, which were 1450 mg $d^{-1}AU^{-1}$ in Europe (Fabbri et al., 2007), and 1100 mg $d^{-1}AU^{-1}$ (Lim et al., 2003) and 690 mg $d^{-1}AU^{-1}$ (Li et al. 2009) in the U.S.

The ADM emission rates agreed fairly well with AHM emission rates, although the hourly data was much more variable than the daily data, resulting in the much larger SDs (Table 15). Daily mean area-specific $PM_{2.5}$ emission rates are plotted in Figure 5.23. Assuming that the distribution of the sampling periods yielded an adequate representation of the entire year, these figures correspond to a mean annual total for all houses at the site of 98±128 g d^{-1} of $PM_{2.5}$, or 36 kg (79 lb) per year.

The patterns of $PM_{2.5}$ emissions in relation to time of day were similar in each house, Figure 5.24. The $PM_{2.5}$ emission rates showed two daily peaks, at approximately 8 am and 5 pm with significant depressions around 11 a.m. and at night beginning at 9 p.m. The hens slept at night which reduced PM emissions in general but the midday depression remains unexplained.

Table 5-23. Average daily $PM_{2.5}$ emission rates derived from daily and hourly mean data.

Variable	House 3	House 4
PM2.5 emission rates from daily means		
House-specific, g d^{-1}	31±77 (21)	165±179(33)
Area-specific, mg $d^{-1}m^{-2}$	9.89±25.1 (21)	52.4±57.6 (33)
Hen-specific, mg $d^{-1}hd^{-1}$	0.33±0.82 (21)	1.78±1.94 (33)
LM-specific, mg $d^{-1}AU^{-1}$	94.9±265 (21)	594±652(33)
PM2.5 emission rates from hourly means		
House-specific, g d^{-1}	35±306 (543)	164±326 (857)
Area-specific, mg $d^{-1}m^{-2}$	11±97 (543)	52±104 (857)
Hen-specific, mg $d^{-1}hd^{-1}$	0.36±3.2 (543)	1.77±3.4 (857)
LM-specific, mg $d^{-1}AU^{-1}$	107±1051 (543)	590±1174 (857)



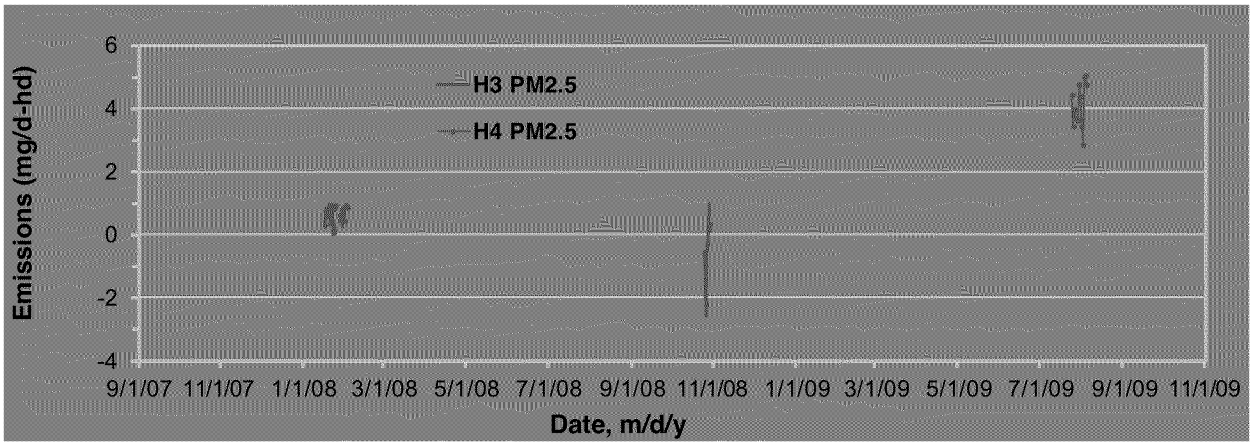


Figure 5.23. Daily means of $PM_{2.5}$ emissions.

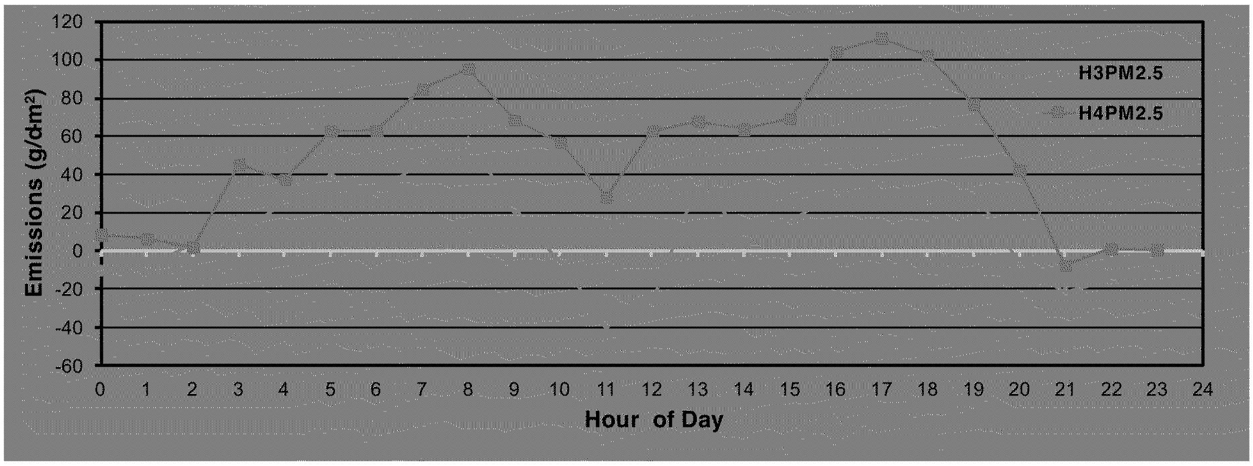


Figure 5.24. Average $PM_{2.5}$ emission by hour of day.

5.6.6.3. TSP Concentration and Emission

Daily mean TSP concentrations are plotted in Figure 5.25. The basic statistics of TSP concentrations in the inlet air and house exhausts are presented in Table 5.-2424. The daily mean TSP concentrations averaged approximately 41±18.9 μg/m^3 in the inlet air, and 1128±834 and 684±652 μg/m^3 in the exhausts of H3 and H4, respectively. Concentrations were highest during a winter sampling event (April, 2009), and lowest during the two high-airflow samplings in Augus, 2008.

The overall mean (±SD) TSP house-specific, hen-specific, area-specific and LM-specific emissions are given in Figure 5.26 and Table 5.-2525. The area-specific daily TSP emissions averaged 1090±481 mg d^{-1} m^{-2} for H3 and 1430±476 mg d^{-1} m^{-2} for H4. The daily and hourly means of TSP emissions were compared in Table 5.-2525. The hourly data was clearly more variable than the daily data, but results in much the same averages as the daily data. The LM-specific ADM TSP emission rates were 12.1±5.45 and 16.3±5.56 g d^{-1}AU^{-1} for H3 and H4, respectively. These values are about three times the mean PM_{10} emission rates. These emission rates are comparable to the 15 g d^{-1}AU^{-1} reported in a European study (Takai et al., 1998), and were also lower than the 44.5 g d^{-1}AU^{-1} from an Ohio layer house (Lim et al., 2007) and 22 g d^{-1}AU^{-1} in a European study (Wathes et al., 1997).

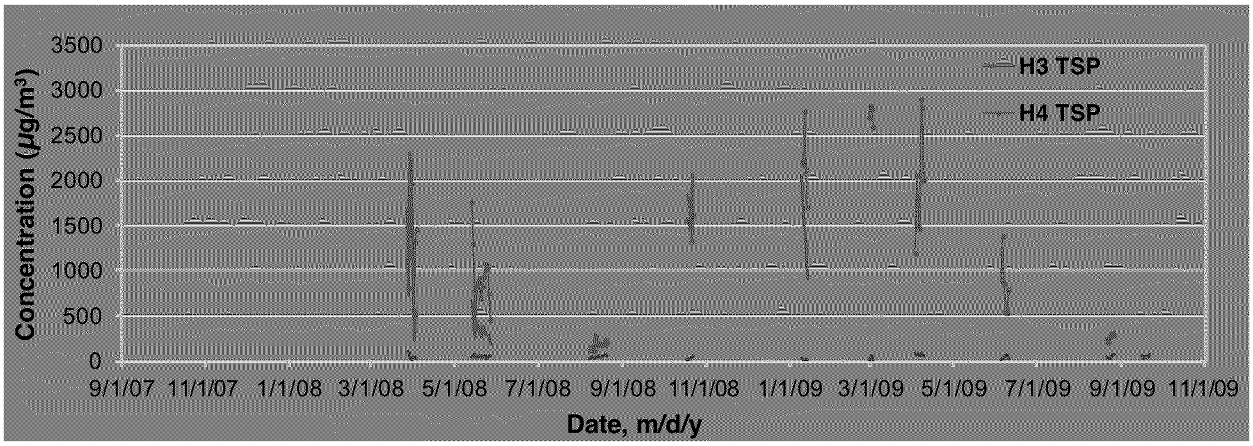


Figure 5.25. Daily means of TSP concentrations.

Table 5-24. Summary of daily mean TSP concentrations.

Variable	Inlet, μg/m^3	H3 Exhaust, μg/m^3	H4 Exhaust μg/m^3
Average Daily Means			
Valid days	90	69	45
Daily min	11	115	112
Daily max	94	2940	2330
2-yr ADM	41.02±18.9	1128±834.1	684.13±652.11
1st yr ADM	42.7±17.9	755.3±556.6	474.8±536.4
2nd yr ADM	39.2±19.75	1534.61±894.36	1521.67±313.85
Average Hourly Means			
Valid hours	2336	1203	1831
Daily min	-46	-133	-99
Daily max	353	5819	7288
2-yr ADM	39.8±30.8	1127±1094	725±873
1st yr ADM	41.8±17.9	772±779	478±655
2nd yr ADM	37.8±33.0	1548±1000.1	1488±1240.5

Figure 5.27 shows the pattern of TSP emissions from H3 and H4 relative to time of day. The emission rate was slightly elevated in both houses at midday, and likely related to changes in animal activity.

Table 5-25. Average daily TSP emission rates derived from daily and hourly means.

Variable	House 3	House 4
TSP emission rates from daily means		
House-specific, g d^{-1}	3433±1515 (45)	4505±1499 (68)
Area-specific, mg d^{-1}m^{-2}	1090±481 (45)	1430±476 (68)
Hen-specific, mg d^{-1}hd^{-1}	35.4±15.6 (45)	48.3±16.3 (68)
LM-specific, mg d^{-1}AU^{-1}	12.1±5.45 (45)	16.3±5.56 (68)
TSP emission rates from hourly means		
House-specific, g d^{-1}	3485±3075 (1189)	4533±3598 (1815)
Area-specific, mg d^{-1}m^{-2}	1106±976 (1189)	1439±1142 (1815)
Hen-specific, mg d^{-1}hd^{-1}	35.9±31.7 (1189)	48.5±38.8 (1815)
LM-specific, g d^{-1}AU^{-1}	12.3±10.8 (1189)	16.5±13.1 (1815)

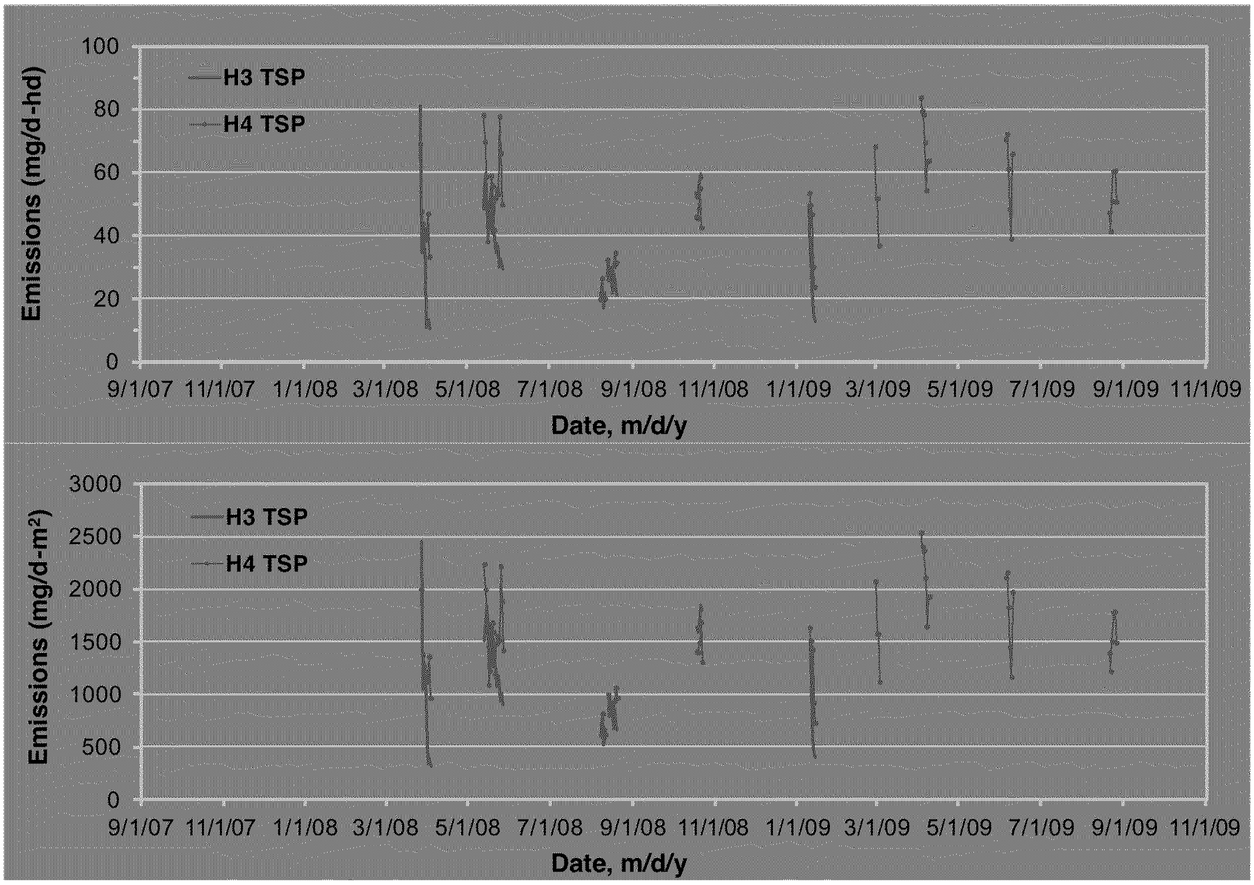


Figure 5.26. Daily means of area-specific TSP emission rates.

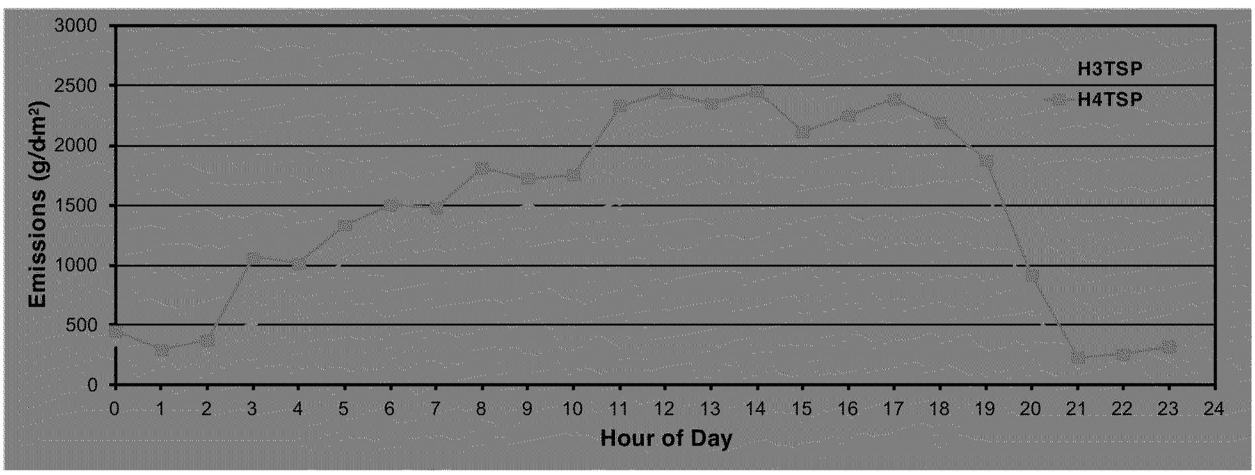


Figure 5.27. Average TSP emission by hour of day.

5.6.7. VOC Concentration and Emission

The VOC emissions in the EPA report (Section 4.5.3) were recalculated using corrected and partitioned airflows (Table 5.-2626). The upstairs (cage area) concentrations were multiplied by the upstairs airflows and the downstairs (pit) concentrations were multiplied by the downstairs (pit) airflows. Fans continuously operated in the pit during each sampling event, but the percentage time that upstairs airflow was greater than zero ranged from 0 to 100%. The concentrations of total VOC in H4 exhaust air were all on the same order of magnitude and averaged 0.42±0.12 mg m^{-3}.

Table 5-26. Emissions of total VOC from H4 (H4) during seven 1-d sampling events.

Date	Conc., mg/m^3		H4 pit	H4 upstairs		H4 emission, kg/d		
	H4 Down	H4 Up	Q, m^3/s	Q, m^3/s	%>0	Pit	Up	Total
4/12/09	0.54	0.45	30.7	0.0	100	1.44	0.00	1.44
4/27/09	0.41	0.42	104	64.3	46.2	3.66	2.35	6.01
5/20/09	0.62	0.54	66.9	5.3	82.3	3.56	0.25	3.80
7/2/09	0.51	0.44	134	93.1	14.6	5.97	3.57	9.54
8/26/09	0.29	0.46	147	131	0	3.68	5.16	8.84
9/9/09	0.26	0.24	132	53.8	28.3	2.98	1.10	4.08
9/18/09	0.41	0.29	105	20.7	58.3	3.70	0.52	4.23
Mean	0.43	0.40	103	52.6	47.1	3.57	1.85	5.42
SD	0.13	0.11	42	48.2	36.0	1.33	1.93	2.91

Single-factor correlation analyses were conducted for the daily VOC emission rates (Table 5.-2727). Factors associated with warm weather (inlet and exhaust temperature, ventilation rate and solar radiation) exhibited strong positive correlations with VOC emission rate.

Table 5-27. Correlation coefficients (r) between H4 VOC emission and various factors.

Inlet temperature	0.895
House airflow	0.808
Exhaust temperature	0.709
Average hen weight	0.457
Solar radiation	0.220
Exhaust relative humidity	0.117
Wind speed	0.025
Hen activity	-0.106
Ambient relative humidity	-0.161
House inventory	-0.285

Because the VOC sampling dates were limited to 7 d during a five month period in 2009, there is potential for significant bias when extrapolating the average results to an annual average. To assess whether potentially important environmental parameters during VOC sampling were representative of the two-year averages, they were compared in Table 5.-2828. The average ambient temperatures during sampling periods were up to 4.6ºC higher than the 2-yr average, but the difference in house exhaust temperatures was only 1.6 ºC. The house airflow during VOC sampling was also higher (156 vs. 111 m^3/s) because of the 4.6ºC higher ambient temperature.

House temperature and airflow showed a strong correlation with VOC emission, thus, calculated VOC emissions factors need some adjustment to account for bias introduced by sampling time. A linear regression of VOC emission (V) and ambient temperature (T) resulted in V = 0.46 T – 4.5 (R^2=0.80). Using this equation to predict the annual average VOC emission based on the historical mean ambient temperature of 15.0°C resulted in V = 0.46 (15.0°C) – 4.5 = 2.40 kg/d.

The hen-specific emission would be 25.6 mg/d-hen. At this rate, it would require about 10.7 million hens to emit 100 tpy and 26.7 million hens to emit 250 tpy.

Table 5-28. Averages of influencing factors during VOC sampling events and 2-yr NAEMS.

Variable	VOC Sampling Period	NAEMS Period
Ambient T, °C	21.6	17.1
Exhaust T, °C	27.7	25.0
Solar radiation, W/m^2	111	123
Inventory, # hens	93,638	92,284
Average wt, kg	1.48	1.42
Density, kg/m^2	44.0	42.4
Airflow, m^3/s	156	112

5.6.8. Nitrogen Balance

A summary of the nitrogen balance calculations for the two manure-storage cycles that fell entirely within the monitoring period (Cycles 2 and 3) is provided in Table 5.-2929. The differences between nitrogen inputs and outputs ranged from 7% to 66%, with an average of 30%. More frequent sampling and analysis of the feed and manure should be conducted in future studies, especially if the objective of applying such a nitrogen balance is to estimate ammonia emission rate.

Table 5-29. Summary of nitrogen balance calculation for houses 3 and 4.

H3	**Date**		**Days**	**Input**		**Output**				**Diff.**
				Feed Characteristics		**Egg Characteristics**		**Manure Characteristics**		**N_{loss} %**
	Start	**End**		**Total kg**	**Total N kg**	**Total Doz**	**Total N kg**	**Total kg**	**Total N kg**	
2	3/15/08	3/26/09	371	2,662,473	78,445	2,325,963	32,615	819,419	21,387	37
3	3/27/09	7/27/09	120	828,309	24,989	628,505	8,813	313,612	8,185	11
H4	**Date**		**Days**	**Input**		**Output**				**Diff.**
				Feed Characteristics		**Egg Characteristics**		**Manure Characteristics**		**N_{loss} %**
	Start	**End**		**Total kg**	**Total N kg**	**Total Doz**	**Total N kg**	**Total kg**	**Total N kg**	
2	3/14/08	3/24/09	370	2,892,917	82,339	2,140,867	30,019	916,696	23,933	66
3	3/25/09	7/27/09	122	1,038,184	27,536	740,788	10,387	400,726	10,459	7

5.6.9. Uncertainties in Airflow and Emission Rate

The quality of the emission rate data is an important issue for agricultural air quality research. Therefore, to estimate the quality of emission rate measurements, the uncertainties in the measured variables that are used in calculating emission rate must be determined. The total uncertainty of any measurement is a combination of systematic and random errors, which are quantified in this report. The emission rate uncertainty arises from the measur uncertainty and variation in components that affect determination of emission such as indoor and ambient environmental conditions, pollutant concentrations and airflow rate. Therefore, uncertainties in airflow, pollutant concentration, indoor air temperature and static pressure contribute to pollutant emission rate uncertainty.

The airflow uncertainty was calculated by using root square mean differences between fan airflow tests and the airflow model derived from the fan-law-adjusted BESS curves, number of fans operating simultaneously, and average airflow rate. Some of these components are given in Table 5.30. Also, ventilation fan stages which controlled house airflow rates were considered in calculating airflow uncertainty. Both houses were ventilated with staged ventilation, with each stage controlling single speed fans of identical model. Houses 3 and 4 controlled 11 stages among a total of thirty-four 122-cm fans.

Table 5-30. The standard deviations of fan tests at NC2B site.

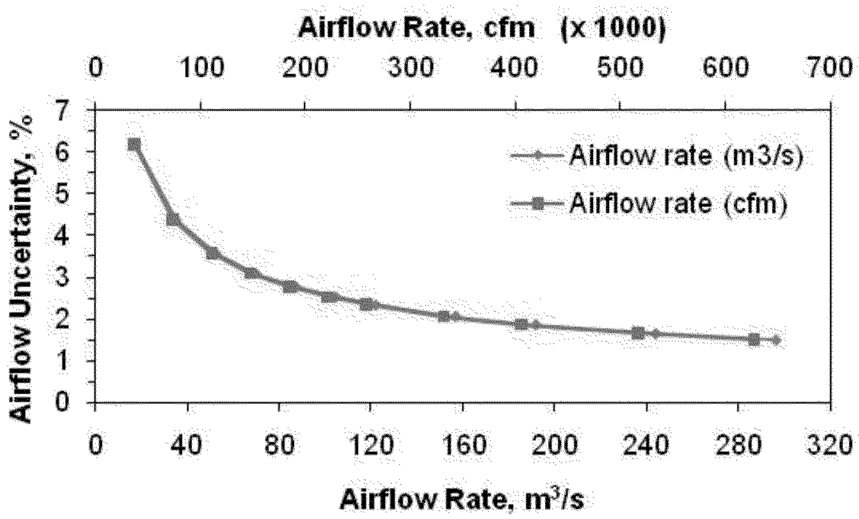
Fan dia, cm	Ref. spd (N_2)	House	Fans/House	Stages	Fan tests		Fan operation	
					n	RMSD	Min	Max
122	570	H3, H4	34	1-11	533	0.382	2	34

The airflow rate uncertainties are shown in Figure 5.28. Airflow rate uncertainties in both of houses ranged from 1.5% to 6.2%, with an average for both houses of 2.9%. Moving from lower to higher stages decreased the standard error or uncertainty, as fan sizes in all stages were same and the number of operating fans (and therefore the total ventilation rate) increased.

Figure 5.29 shows the dependence of emission rate (ER) uncertainty on house airflow for all houses. The pattern of emission rate uncertainties is similar to the airflow rate uncertainty, as the total airflow rate accounted for most of the uncertainty in calculations of emissions (Table 5.-3131). Uncertainties in concentration measurements were comparatively small. The ER uncertainties for H3 and H4 decreased with increased airflow rate. The overall averages of ER uncertainties were 5.8% for NH_3, 12.2% for H_2S, 14.0% for PM10 and PM2.5, 14.7% for TSP.

Table 5-31. Averages and ranges of emission rate uncertainties.

Pollutant	Range, %		Average, %	
	H3	H4	H3	H4
NH_3	5.1 - 7.87	5.1 - 7.87	5.8	5.8
H_2S	11.8 - 13.3	11.8 - 13.3	12.2	12.2
PM_{10}	13.9 - 15.2	13.6 - 14.9	14.2	13.9
$PM_{2.5}$	13.9 - 15.2	13.6 - 14.9	14.2	13.9
TSP	14.6 - 15.8	14.3 - 15.5	14.9	14.5



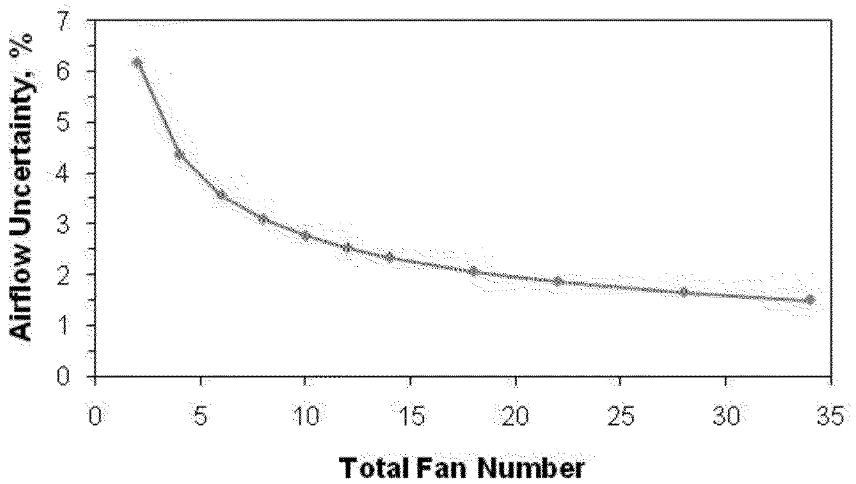
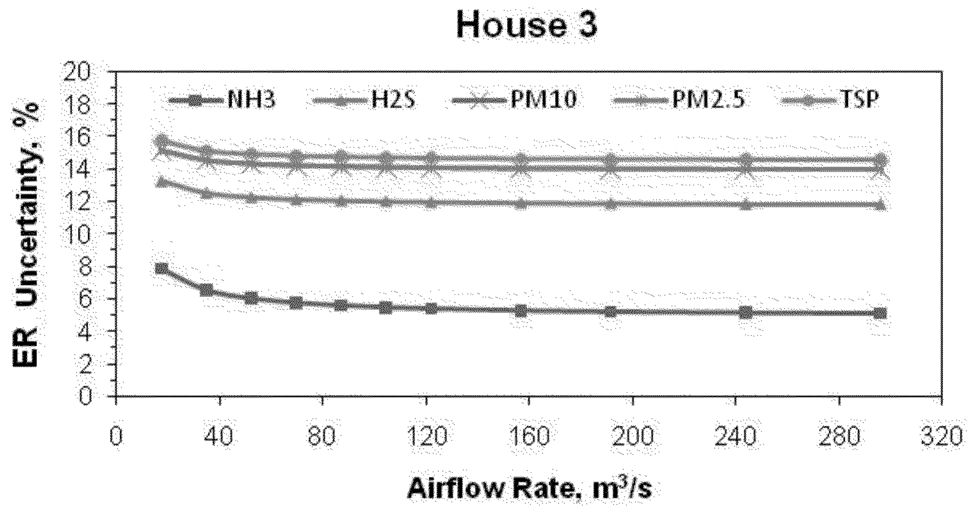


Figure 5.28. The variation of uncertainty in total airflow rate.



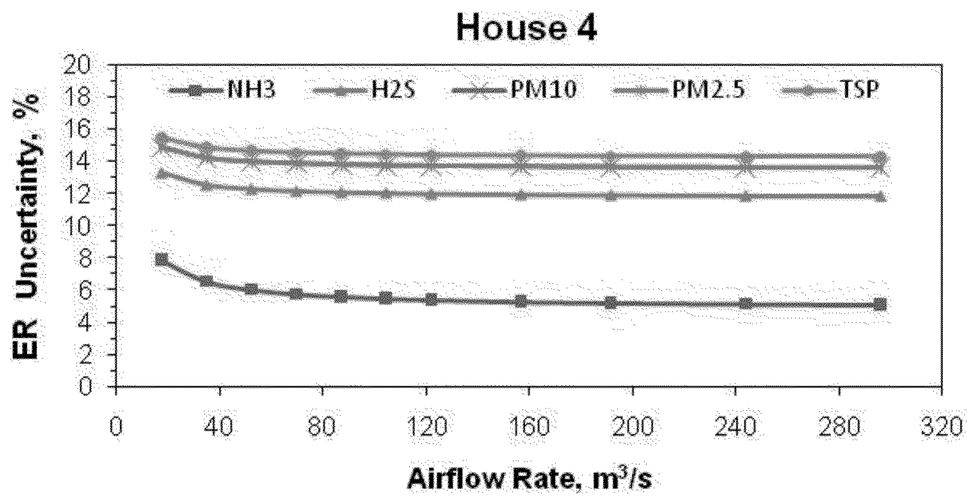


Figure 5.29. The variation of emission rate uncertainty for individual houses.

6. SIZE OF FARMS THAT EXCEED REGULATORY THRESHOLDS

The Clean Air Act established a threshold emission limit of 250 tons per year (tpy) of any criteria air pollutant in areas of compliance and 100 tpy in areas of non-compliance. The U.S. EPA and state air pollution regulatory agencies use emission factors in the air pollution regulatory process to determine the emissions inventory for the operation (tons per year), and to estimate the downwind concentration that might be expected from the operation.

The¬ annual¬ emissions¬ inventories¬ are¬ used¬ to¬ determine¬ whether¬ the¬ c
source”.¬ For¬ example,¬ any¬ point¬ source¬ in¬ attainment¬ area¬ that¬ emits¬
regulated pollutant is classified as a major source and must pay an annual emission fee to the respective¬ state’s¬ air fund (Sweeten et al., 2000).

However, the Emergency Planning and Community Right-to-Know Act (EPCRA) has reporting requirements¬ of¬ 100¬ lb/d¬ of¬ single¬ “hazardous¬ substance”¬ or¬ 18.3¬ tpy
large facilities (Miles et al., 2004; Anonymous, 2010; Centner and Patel, 2010). The EPCRA requires upper and lower limits on estimates and the reporting requirement is based upon the upper limit. Failure to report can result in fines of $25K/d for noncompliance and possible criminal charges, punishable by up to five years in jail (Anonymous, 2010).

Relative to aerial emissions from confined animal feeding operations and according to federal reference, a hazardous substance means NH_3, particulate matter (PM) and other aerial pollutants in the poultry industry. The U.S. EPA (1987, 40CFR50) replaced the total suspended particulate (TSP) standards for all sources in the U.S. with a PM_{10} standard based on PM having mass median diameter of 10 microns (μm). In essence, the revision was based on the premise that relatively fine, rather than coarse dust, needs to receive greater focus in protecting human health. The PM_{10} primary and secondary 24-h standards were changed to 150 $\mu g/m^3$ for a 24-h average with no more than one exceedance per year (Sweeten et al., 2000).

The following sections present the findings of the numbers of hens that exceed 100 lb/d for NH_3 and H_2S, and 250 tons per year for VOC and PM_{10} based on the NAEMS monitoring results at the four layer hen sites. The calculation methodologies were as follows:

For all the monitoring sites:

1. All calculations were conducted on the complete-day data, which were defined as data only from days with greater than 75% valid data.
2. The average daily mean (ADM) hen-specific VOC emission from each house was calculated by a) obtaining the average VOC emission of the house measured during up to seven sampling events, and b) dividing the average VOC by the ADM hen inventory.

For the high-rise sites (CA2B, IN2H, and NC2B):

3. <u>The ADM (average daily mean) hen-specific emission from each house</u>, except for VOC, was calculated by a) obtaining each daily mean (DM) hen-specific emissions, and b)

averaging all the DM hen-specific emissions over the 2-yr test. These values are the same as presented in the previous chapters of this report.

4. The NEET (number to exceed emission threshold) for a high-rise house was calculated by a) obtaining the ADM emission of the house, b) obtaining the ADM house inventory, c) dividing the ADM emission of the house by the ADM house inventory, and d) comparing the hen specific emission with the reportable quantity of 100 lb/d. Empty house emissions, when available, were included in the calculation of the NEET.
5. The site (with multiple houses) ADM hen-specific emission and the site NEET were the arithmetic means of two-house ADM hen-specific emissions and the NEET, respectively.
6. The mean NEET was the arithmetic mean of the NEETs at the three high-rise sites.

For the manure-belt site (IN2B):

7. The ADM hen-specific emission from each house, except for VOC, was calculated by a) obtaining each daily mean (DM) hen-specific emission rate, and b) averaging all the DM hen-specific emissions over the 2-yr test. These values are the same as presented in the previous chapters of this report.
8. The ADM hen-specific emission from the manure shed was calculated by a) obtaining each daily mean (DM) hen-specific emission by dividing the daily total emission by the total number of hens in both houses, and b) averaging all the DM hen-specific emissions over the 2-yr test. These values are the same as presented in the previous chapters of this report.
9. The NEET for the manure-belt site was calculated by a) obtaining ADM emission of both houses and the manure shed, b) obtaining ADM house inventories, c) dividing the ADM emission of the houses and the shed by the ADM number of hens of both houses, and d) comparing the hen-specific emission with 100 lb/d. Empty house and manure shed emissions, when available, were included in the calculation of the NEET.
10. The mean NEET equals the NEET for the manure-belt site.

6.1. Ammonia

6.1.1. High-Rise Sites

At the three high-rise sites (CA2B, IN2H, and NC2B), hen-specific emissions varied considerably for NH_3 (Table 6-16.1) but were very consistent between replicated houses at each site. The average daily means (ADM) ranged from 0.596 g/d-hen from NC2B H3 to 1.126 g/d-hen from IN2H H7 (excluding empty house periods). Consequently, the NEET for NH_3 at each site ranged from 41,979 to 74,740 hens (including empty house periods). The mean NEET for NH_3 at the three sites was 54,228 hens.

Table 6-1. Mean NH_3 emission and NEET for the high-rise sites at 100 lb/d.

CA2B	House 5	House 6	Site
ADM emission, g/d-hen	0.952	0.944	0.948
NEET, hens	45,932	45,995	45,964
IN2H	**House 6**	**House 7**	**Site**
ADM emission, g/d-hen	1.024	1.142	1.083
NEET, hens	44,243	39,715	41,979
NC2B	**House 3**	**House 4**	**Site**
ADM emission, g/d-hen	0.596	0.620	0.608
NEET, hens	75,816	73,664	74,740
Mean NEET, hens			54,228

6.1.2. Manure-Belt Site

Compared with the high-rise sites, the ADM NH_3 emissions from the manure-belt site (IN2B) were much lower (Table 6-26.2.). The ADM hen-specific emission rate was 0.289 g/d-hen, including the manure shed. The NEET was 157,437 hens.

Table 6-2. Mean NH_3 emission and NEET for the manure-belt site at 100 lb/d.

IN2B	House 8	House 9	Shed	Site
ADM emission, g/d-hen	0.282	0.277	0.009	0.289
NEET, hens				157,437

6.2. Hydrogen Sulfide

6.2.1. High-Rise Sites

Hydrogen sulfide exhibited large variations in hen specific emissions among different sites but were similar between replicated houses. The ADM emission rates ranged from 0.61 mg/d-hen from NC2B H3 to 1.46 mg/d-hen from IN2H H6 (Table 6-36.3). The NEET at the three sites ranged from 32.99 million hens (IN2H) to 70.15 million hens at NC2B. The mean NEET for the three sites was 45.99 million hens.

Table 6-3. Mean H_2S emission and NEET for the high-rise sites at 100 lb/d.

CA2B	House 5	House 6	Site
ADM emission, mg/d-hen	1.33	1.20	1.27
NEET, hens	33,061,577	36,570,383	34,815,980
IN2H	**House 6**	**House 7**	**Site**
ADM emission, mg/d-hen	1.47	1.37	1.41
NEET, hens	30,856,620	33,108,928	31,982,774
NC2B	**House 3**	**House 4**	**Site**
ADM emission, mg/d-hen	0.61	0.68	0.65
NEET, hens	74,215,455	66,090,062	70,152,758
Mean NEET, hen			45,650,504

6.2.2. Manure-Belt Site

The ADM H_2S emission from the manure-belt houses of 2.02 mg/d-hen (including manure shed, but excluding empty house days) was a little higher than the high-rise houses (Table 6-46.4). The

NEET for H_2S at this site was 22.47 million hens, less than half of the mean NEET of the three high-rise sites, but still several times larger than the largest known egg producing operation.

Table 6-4. Mean H_2S emission and NEET for the manure-belt site at 100 lb/d.

IN2B	House 8	House 9	Shed	Site
ADM emission, mg/d-hen	1.95	1.96	0.07	2.02
NEET, hens				22,469,537

6.3. Particulate Matter (PM_{10})

6.3.1. High-Rise Sites

The ADM emissions of PM_{10} ranged from 16.2 mg/d-hen from H3 at NC2B to 37.6 mg/d-hen from H5 at CA2B (Table 6-56.5Table 6-56.5). Compared with the 250 tpy PM_{10} emission threshold, the NEETs were very large, ranged from 17.8 million (H5 at CA2B) to 43.2 million (H3 at NC2B) hens. The NEET for the three sites ranged from 20.36 to 35.52 million hens. The mean NEET for the three sites was 30.42 million hens.

Table 6-5. Mean PM_{10} emission and NEET for the high-rise sites at 250 tpy.

CA2B	House 5	House 6	Site
ADM emission, mg/d-hen	37.6	29.2	33.4
NEET, hens	17,798,287	22,929,733	20,364,010
IN2H	**House 6**	**House 7**	**Site**
ADM emission, mg/d-hen	16.9	22.6	19.8
NEET, hens	40,471,405	30,300,587	35,385,996
NC2B	**House 3**	**House 4**	**Site**
ADM emission, mg/d-hen	16.2	24.0	20.09
NEET, hens	43,172,580	27,873,778	35,523,179
Mean NEET, hens			30,424,395

6.3.2. Manure-Belt Site

The ADM emission rates from IN2B were 12.4, 25.2, and 0.3 mg/d-hen from H8, H9, and the shed, respectively. There was more than a 100% difference between houses (Table 6-66.6). When the emissions from the shed were included and shared by both houses, the ADM emission was 19.1 mg/d-hen and the NEET was 36.24 million hens.

Table 6-6. Mean PM_{10} emission and NEET for the manure-belt site at 250 tpy.

IN2B	House 8	House 9	Shed	Site
ADM emission, mg/d-hen	12.4	25.2	0.3	19.1
NEET, hens				36,244,732

6.4. Volatile Organic Compounds (VOC)

6.4.1. High-Rise Sites

Some errors were corrected in the calculations of VOC emissions reported in the EPA report for the Indiana layer sites IN2H and IN2B due to incorrect airflows used in the calculations. Also, in the following presentation, the first set of IN2H samples taken January 9, 2009 were removed from the data because of the extreme outlier in H6 (95.3 kg/d) and this was the VOC VOC sample taken for the NAEMS which occurred two months before the second set of samples. The annual VOC emissions were calculated from average VOC emissions for each site by an inlet temperature regression to the historical average ambient temperatures for the areas provided the regression was significant and that the average ambient temperature during VOC sampling was different than the historical average. These adjusted VOC emissions are referred to as annualized VOC emission rates.

The annualized total VOC emissions ranged from 25.6 mg/d-hen from NC2B (H4) to 83.3 mg/d-hen from house 5 at CA2B (Table 6-76.7). There was only about a 3-fold difference in annualized ADM total VOC after removing an extreme outlier during one CA2B sampling event. The VOC NEET for the three sites ranged from 9.7 million to 26.7 million hens. The mean annualized emission rate for high rise houses was 58.6 mg/d-hen which translates to a VOC NEET of 11.7 million hens. The estimated VOC NEET is 4.7 million hens for the 100 tpy threshold.

Table 6-7. Annualized VOC emission and NEET for the high-rise sites at 250 tpy. The CA2B and IN2H annualized emissions were calculated without the 10/2/09 and 1/9/09 outliers, respectively.

CA2B	**House 5**	**House 6**	**Site**
ADM emission, mg/d-hen	76.3	66.3	71.3
NEET, hens	8,971,227	10,330,638	9,603,062
IN2H	**House 6**	**House 7**	**Site**
ADM emission, mg/d-hen	83.3	74.4	78.8
NEET, hens	8,222,118	9,209,137	8,687,684
NC2B	**House 3**	**House 4**	**Site**
ADM emission, mg/d-hen	-	25.6	25.6
NEET, hens	-	26,723,174	26,723,174
Average High-Rise			
ADM emission, mg/d-hen			58.6
NEET, hens			11,688,632

6.4.2. Manure-Belt Site

The annualized VOC emission from the manure-belt site of 59.6 mg/d-hen (Table 6-86.8) was somewhat less than the IN2H and CA2B sites but over twice as high as NC2B. The emissions were essentially identical to the average of the three high-rise sites,. The VOC NEET from this site was 11.5 million hens compared with 11.7 million hens for high rise houses. Thus the overall average VOC NEET was 11.6 million hens among all types.

Table 6-8. Mean VOC emissions and NEET for the manure-belt site at 250 tpy.

IN2B	**House 8**	**House 9**	**Site**
ADM emission, mg/d-hen	57.2	61.9	59.6
NEET, hens	11,967,289	11,071,086	11,519,188

6.5. Summary

The average mean numbers of hens exceeding EPCRA reportable quantities for the four pollutants are summarized in Table 6-96.9. Data presented in the table are rounded with only three significant digits. There are many layer hen CAFO (concentrated animal feeding operation) exceeding the reporting threshold for ammonia emissions (100 lb/d). Very few, if any, farms are large enough to exceed the reporting thresholds for H_2S (100 lb/d), PM_{10} (250 tons/year) and VOC (250 tpy).

Table 6-9. Summary of average NEET for NH_3, H_2S, VOC and PM_{10} for all sites.

Pollutant	High-rise mean NEET, hens	Manure-belt NEET, hens
Ammonia (100 lb/d)	54,200	157,000
Hydrogen sulfide (100 lb/d)	46,000,000	22,500,000
PM_{10} (250 tpy)	30,400,000	36,200,000
VOC (250 tpy)	11,700,000	11,500,000

7. DEFINITIONS AND ACRONYMS

A	Area, m^2
ADM	Average daily mean
ACGIH	American Conference of Governmental Industrial Hygienists
AHM	Average hourly mean
APECAB	Air Pollutant Emissions from Confined Animal Buildings
AU	Animal unit = 1,100 lb (500 kg) live mass or weight.
H1, H2	Layer houses 1, 2
CAFO	Concentrated animal feeding operations
CAPECAB	Calculations of Air Pollutant Emissions from Confined Animal Buildings
CEM	Continuous emissions monitoring
CERCLA	Community Emergency Response Act
CI	Confidence interval
CH_4	Methane
CO_2	Carbon dioxide
d	Day
DM	Daily mean
dP	Differential static pressure, difference between inside and outside pressure
doz	Dozen eggs
E	Emission rate
EPCRA	Emergency Planning and Community Right-to-Know Act
ER	Emission rate
F	Fan
FANS	Fan Airflow Numeration System
h	Hour
H_2S	Hydrogen sulfide
IN2B	Layer site in Indiana with manure belt houses
IN2H	Layer site in Indiana with high rise houses
LM	Live mass, kg
LMD, D	Live mass density, kg/m^2
mi	Miles
MPC	Multipoint calibration
MSA	Mine Safety Applicance, Inc.
MSD	Mass selection detector
N	Nitrogen or fan speed, rpm
n	Number or count
NAEMS	National Air Emissions Monitoring Study
NC2B	Layer houses in North Carolina
CA2B	Layer houses in California
NCSU	North Carolina State University
NE	Northeast
NEET	Number to exceed emission threshold
NH_3	Ammonia
OSHA	Occupational Safety and Health Administration

PM	Particulate matter
$PM_{2.5}$	PM less than 2.5 µm diameter
PM_{10}	PM less than 10 µm diameter
ppb	Parts per billion
ppm	Parts per million
Q	House airflow, m^3/s
QA	Quality assurance
QC	Quality control
r	Pearson correlation coefficient
RE	Relative error, %
RH/T	Relative humidity/temperature
RH	Relative humidity
RMSD	Root mean square deviation
s	Second
SD	Standard deviation
SE	Standard error
T	Temperature, °C
T_{dew}	Dew point temperature, °C
TEOM	Tapered element oscillating microbalance
TKN	Total Kjeldahl nitrogen
tpy	Tons per year
TSP	Total suspended particulate
VOC	Volatile organic compounds
VS	Volatile solids
USEPA	United States Environmental Protection Agency
yr	Year
Z/S	Zero/span

8. REFERENCES

Anonymous. 2010. *CERCLA/EPCRA Reporting Frequently Asked Questions*. Little Rock, Arkansas: University of Arkansas Cooperative Extension Service, http://www.aragriculture.org/air/cercla_epcra_reporting/frequent_questions.htm. Accessed 31 October, 2010.

Banhazi, T. M., J. Seedorf, M. Laffrique, and D. L. Rutley. 2008. Identification of the risk factors for high airborne particle concentrations in broiler buildings using statistical modelling. *Biosystems Engineering* 101(1):100-110.

Battye, W., V.P. Aneja, and P.A. Roelle. 2003. Evaluation and improvement of ammonia emissions inventories. *Atmospheric Environment* 37(27):3873-3883.

Blanes, V. and S. Pedersen. 2005. Ventilation flow in pig houses measured and calculated by carbon dioxide, moisture and heat balance equations. *Biosystems Engineering* 92(4):483-493.

Bottcher, R.W., K.M. Keener, R.D. Munilla, C.M. Williams, and S.S. Schiffman. 2004. Dust and odor emissions from tunnel ventilated swine buildings in North Carolina and comparison of different odor evaluation methods. *Applied Engineering in Agriculture* 20(3):343-347.

Centner, T.J. and P.G. Patel. 2010. Reporting air emissions from animal production activities in the United States. *Environment International* 36(3):237-242.

Chai, C.A., J.-Q. Ni, , Y. Chen, C.A. Diehl, A.J. Heber, and T.-T. Lim. 2010. Assessment of long-term gas sampling design at two commercial manure-belt layer barns. *Journal of AWMA* 60:702-710.

Chai, L., J.-Q. Ni, C.A. Diehl, I. Kilic, A.J. Heber, Y. Chen, E.L. Cortus, B.W. Bogan, T.T. Lim, J.-C. Ramirez-Dorronsoro, and L. Chen. 2012. (In Press). Ventilation rates at large commercial layer houses with two-year continuous monitoring. *British Poultry Science* 53(1):19-31.

Chen, Y., J.-Q. Ni, C.A. Diehl, A.J. Heber, W.W. Bogan, and L. Chai. 2011. Large scale application of vibration sensors for fan monitoring at commercial layer hen houses. *Sensors* 10(12):11590-11604.

Cheng, W. C., W. H., M. S. Chou, and S. C. Tung. 2011. Gaseous ammonia emission from poultry facilities in Taiwan. *Environmental Engineering Science* 28(4):283-289.

Dobeic, M. and S. Pintaric. 2011. Laying hen and pig livestock contribution to aerial pollution in Slovenia. *Acta Veterinaria-Beograd* 61(2-3):283-293.

Dobeic, M. and S. Pintaric. 2011. Laying hen and pig livestock contribution to aerial pollution in Slovenia. *Acta Veterinaria-Beograd* 61(2-3):283-293.

Ellen, H. H., R. W. Bottcher, E. vonWachenfelt, and H. Takai. 2000. Dust levels and control methods in poultry houses. *Journal of Agricultural Safety and Health* 6(4):275-282.

Fabbri, C., Valli, L., Guarina, M., Costa, A., Mazzotta, V. 2007. Ammonia, methane, nitrous oxide and particulate matter emissions from two different buildings for laying hens. *Biosystems Engineering* 97(4):441-455.

Gates, R.S., K.D. Casey, H. Xin, E.E. Wheeler, and J.D. Simmons. 2004. Fan Assessment Numeration System (FANS) design and calibration specifications. *Transactions of the ASAE* 47:1709-1715.

Gay, S. W., E. F. Wheeler, J. L. Zajaczkowski, and P. A. Topper. 2005. Ammonia emissions from U.S. tom turkey grow out and brooder houses under cold weather mechanical ventilation. Paper #054034. Presented at the 2005 ASAE Annual International Meeting, Tampa, Florida. ASAE, St. Joseph, Michigan.

Gay, S.W., D.R. Schmidt, C.J. Clanton, K.A. Janni, L.D. Jacobson, and S. Weisberg. 2003. Odor, total reduced sulfur, and ammonia emissions from animal housing facilities and manure storage units in Minnesota. *Applied Engineering in Agriculture* 19(3):347-360.

Gooch, C.A., K.J. Czymmek, and F. Mitloehner. 2011. Dairy emissions: After the NAEMS study, what's up, and what's next? Dairy Business, March. [http://dairybusiness.com/archive/?p=9848]

Green, A.R., I. Wesley, D.W. Trampel, and H. Xin. 2009. Air quality and hen health status in three types of commercial egg layer houses. *Journal of Applied Poultry Research* 18(3):605-621.

Heber, A.J., B.W. Bogan, J.Q. Ni, T.T. Lim, E.L. Cortus, J.C. Ramirez-Dorronsoro, C.A. Diehl, S.M. Hanni, C. Xiao, K.D. Casey, C.A. Gooch, L.D. Jacobson, J.A. Koziel, F.M. Mitloehner, P.M. Ndegwa, W.P. Robarge, L. Wang and R. Zhang. 2008. The National Air Emissions Monitoring Study: Overview of barn sources. Paper presented at the Eighth International Livestock Environment Symposium, Iguassu Falls, Brazil, Sept. 1-5.

Heber, A.J., J.Q. Ni, B.L. Haymore, R.K. Duggirala, and K.M. Keener. 2001. Air quality and emission measurement methodology at swine finishing buildings. *Transactions of the ASAE* 44(6):1765-1778.

Heber, A.J., J.-Q. Ni, E.L. Cortus, T.-T. Lim, and B.W. Bogan. 2011. National study of livestock air quality in USA. Proc. Int. Symp. on Health Environment and Animal Welfare (ISHEAW-2011).

Heber, A.J., J.-Q. Ni, T.-T. Lim, R. Chervil, P.C. Tao, L.D. Jacobson, S.J. Hoff, J.A. Koziel, Y. Zhang, D.B. Beasley, and J.M. Sweeten. 2005. Aerial pollutant emissions from two high-rise layer barns in Indiana. In *A&WMA's 98th Annual Conference & Exhibition* Minneapolis, Minnesota. Paper # 1368. A&WMA, Pittsburgh, PA.

Heber, A.J., T.T. Lim, J.-Q. Ni, P.-C. Tao, A.M. Schmidt, J.A. Koziel, S.J. Hoff, L.D. Jacobson, Y. Zhang, and G.B. Baughman. 2006. Quality assured measurements of animal building emissions: Particulate matter concentrations. Journal of the Air & Waste Management Association 56:1642-1648.

Helbacka, N.V., C.J. Smith, and J.L. Casterline. 1963. Effect of high CO2 atmosphere on laying hen. *Poultry Science* 42(5):1082-1084.

Hutchings, N., B. Amon, U. Dämmgen, and J. Webb. 2009. Animal husbandry and manure management. In EMEP/EEA air pollutant emission inventory guidebook. European Environment Agency, Copenhagen, Denmark.

Koerkamp, P.W.G.G., J.H.M. Metz, G.H. Uenk, V.R. Phillips, M.R. Holden, R.W. Sneath, J.L. Short, R.P. White, J. Hartung, J. Seedorf, M. Schroder, K.H. Linkert, S. Pedersen, H. Takai, J.O. Johnsen, and C.M. Wathes. 1998. Concentrations and emissions of ammonia in livestock buildings in Northern Europe. *Journal of Agricultural Engineering Research* 70(1):79-95.

Li, H., H. Xin, Y. Liang, R. S. Gates, E. F. Wheeler, A. J. Heber. 2005. Comparison of direct vs. indirect ventilation rate determinations in layer barns using manure belts. Transactions of the ASAE 48(1): 367-372.

Li, Q., L. Wang-Li, Z. Liu and A.J. Heber. 2012. Field evaluation of particulate matter measurements using Tapered Element Oscillating Microbalance in a layer house. Journal of AWMA. DOI: 10.1080/10473289.2011.650316.

Li, Q.-F., L. Wang-Li, B. W. Bogan, K. Wang, I. Kilic, J-Q. Ni, and A. J. Heber. (Under preparation). National Air Emissions Monitoring Study-Southeast layer site: Part II- particulate matter. *Transactions of the ASABE.*

Li, Q.-F., L. Wang-Li, B.W. Bogan, K. Wang, J-Q. Ni, and A.J. Heber. (Under preparation). National Air Emissions Monitoring Study-Southeast layer site: Part IV- impacts of the house management practices. *Transactions of the ASABE.*

Li, S., H. Li, H. Xin, R.T. Burns, 2009. Particulate Matter Emissions from a High-rise Layer House in Iowa. 2009 ASABE Annual International Meeting, June 21 – June 24, Grand Sierra Resort and Casino, Reno, Nevada.

Liang, Y., H. Xin, A. Tanaka, S.H. Lee, H. Li, E.G. Wheeler, R.S. Gates, J.S. Zajaczkowski, P. Topper, and K.D. Casey. 2003. Ammonia emissions from layer houses in Iowa. In *International Symposium on Control of Gaseous and Odor Emissions from Animal Production Facilities*. Horsens, Denmark, June 2-4. Danish Institute of Agricultural Sciences: Foulum, Denmark. p. 203-212.

Liang, Y., H. Xin, E.F. Wheeler, R.S. Gates, H. Li, J.S. Zajaczkowski, P.A. Topper, K.D. Casey, B.R. Behrends, D.J. Burnham, and F.J. Zajaczkowski. 2005. Ammonia emissions from US laying hen houses in Iowa and Pennsylvania. *Transactions of the ASAE* 48(5):1927-1941.

Liang, Y., H. Xin, E.F. Wheeler, R.S. Gates, H. Li, J.S. Zajaczkowski, P.A. Topper, K.D. Casey, B.R. Behrends, D.J. Burnham, and F.J. Zajaczkowski. 2005. Ammonia emissions from US laying hen houses in Iowa and Pennsylvania. *Transactions of the ASAE* 48(5):1927-1941.

Lim, T.-T., A.J. Heber, and J.-Q. Ni. 2003. Air quality measurements at a laying hen house: odor and hydrogen sulfide emissions. In *International Symposium on Control of Gaseous and Odor Emissions from Animal Production Facilities*. Horsens, Denmark, June 2-4. Danish Institute of Agricultural Sciences: Foulum, Denmark. p. 273-282.

Lim, T.-T., A.J. Heber, and J.-Q. Ni. 2004. Air quality measurements at a laying hen house: ammonia concentrations and emissions. In *A&WMA's 97th Annual Conference & Exhibitio* Indianapolis, Indiana, June 22-25. A&WMA, Pittsburgh, PA. p. 9.

Lim, T.-T., A.J. Heber, E.C. Hale III, J.-Q. Ni, and L. Zhao. 2008. Effects of EcoCal(TM) on ammonia emission from a high-rise layer rarn. In *Mitigation Air Emissions from Animal Feeding Operations*. Des Moines, Iowa, May 19-20, eds, E. Muhlbauer, L. Moody, and R. Burns. p. 139-143.

Lim, T.T., A.J. Heber, J.-Q. Ni, J.X. Gallien and H. Xin. 2003. Air quality measurements at a laying hen house: Particulate matter concentrations and emissions. In Proceedings of the Air Pollution and Agricultural Operations III. St. Joseph,MI: ASABE. 7 p.

Lim, T.T., Sun,H., Ni, J.Q., Zhao, L., Diehl, C.A., Heber, A.J., Hanni, S.M. 2007. Field tests of a particulate impaction curtain on emissions from a high-rise layer house. Trans. ASABE 50(5): 1795.

Lin, X.-J., E.L. Cortus, R. Zhang, S. Jiang, and A.J. Heber. 2012. The ammonia, hydrogen sulfide, carbon dioxide and particulate matter emissions from commercial high-rise layer buildings. *Atmospheric Environment* 46: 81-91.

Miles, D.M., P.R. Owens, and K.R. Sistani. 2004. *Air emission standards: Poultry production and ammonia*. Proceedings of the Poultry Federation Annual Poultry Symposium, http://www.ars.usda.gov/research/publications/publications.htm?seq_no_115=164404. Accessed 10 April, 2009.

National Climatic Data Center. 1981. Comparative Climatic Data for the United States through 1980. National Oceanic and Atmospheric Administration, Department of Commerce.

National Climatic Data Center. 1998. Climatic wind data for the United States. National Oceanic and Atmospheric Administration, Department of Commerce. http://www.ncdc.noaa.gov/oa/documentlibrary/wind/wind1996.pdf.

Ni, J.-Q. and A.J. Heber. 2008. Chapter 4: Sampling and measurement of ammonia at animal facilities. *Advances in Agronomy* 98:201-269.

Ni, J.-Q. and A.J. Heber. 2010. An on-site computer system for comprehensive agricultural air quality research. *Computers and Electronics in Agriculture* 71(1):38-49.

Ni, J.-Q., A.J. Heber, M.J. Darr, T.T. Lim, C.A. Diehl, and B.W. Bogan. 2009. Air quality monitoring and on-site computer system for livestock and poultry environment studies. *Transactions of the ASABE* 52(3): 937-947.

Ni, J.-Q., A.J. Heber, S.M. Hanni, T.-T. Lim, and C.A. Diehl. 2010. Characteristics of ammonia and carbon dioxide releases from layer hen manure. *British Poultry Science* 51(3):326-334.

Ni, J.-Q., E.L. Cortus, and A.J. Heber. 2011. Improving ammonia emission modeling and inventories by data mining and intelligent interpretation of comprehensive agricultural air quality databases. *Atmosphere* 2(2):110-128.

Ni, J.-Q., L. Chai, B.W. Bogan, K. Wang, E.L. Cortus, A.J. Heber, T.T. Lim and C.A. Diehl. (Submitted 1/24/12). Characteristics of ammonia, hydrogen sulfide, carbon dioxide, and particulate matter concentrations in high-rise and manure-belt layer hen houses. *Atmospheric Environment.*

Nicholson, F.A., J. Chambers, and A.W. Walker. 2004. Ammonia emissions from broiler litter and laying hen manure management systems. *Biosystems Engineering* 89(2):175-185.

NIOSH. 2005. NIOSH Pocket Guide to Chemical Hazards. http://www.cdc.gov/niosh/npg/npgd0028.html>. Accessed 10-30-10.

NRC. 2003. *Air Emissions from Animal Feeding Operations: Current Knowledge, Future Needs*. Washington, DC: The National Academies Press. 286 p.

Roumeliotis, T.S and B.J. Van Heyst. 2008. Summary of ammonia and particulate matter emission factors for poultry operations. Journal of Applied Poultry Research 17: 305-314.

Schutz, M., T. Applegate, B. Richert, A. Sutton, and D. Jones. 2005. Air Emissions Consent Agreement and National Air Emissions Monitoring Study - How Do They Affect Me? Purdue University, West Lafayette, IN.

Sun, H., T.T. Lim, A.J. Heber, L. Zhao, J.-Q. Ni, C.A. Diehl, P.C. Tao, and S.M. Hanni. 2005. Ammonia emissions from a belt-battery layer house. In *ASAE Annual International Meeting*. Tampa Convention Center, Tampa, Florida, 17 - 20 July. St. Joseph, Mich.: ASAE.

Sweeten, J.M., L. Erickson, P. Woodford, C.B. Parnell, K. Thu, T. Coleman, R. Flocchini, C. Reeder, J.R. Master, W. Hambleton, G. Bluhm, and D. Tristao. 2000. Air quality research and technology transfer white paper and recommendations for concentrated animal feeding operations. USDA Agricultural Air Quality Task Force, Washington D.C. July 19.

Takai, H., Pedersen, S., Johnsen, J.O., Metz, J.H.M., Koerkamp, P.W.G.G., Uenk, G.H., Phillips, V.R., Holden, M.R., Sneath, R.W., Short, J.L., White, R.P., Hartung, J., Seedorf, J., Schroder, M., Linkert, K.H., Wathes,C.M.1998. Concentrations and emissions of airborne dust in livestock buildings in Northern Europe. J. Agric. Engng Res. 70: 59-77.

UEP. 2010. Animal husbandry guidelines for US egg laying flocks, 2010 edition. <http://www.unitedegg.org/information/pdf/UEP_2010_Animal_Welfare_Guidelines.pdf>. Accessed 3-23-11.

Wang, K., Q. -F. Li, B.W. Bogan, I. Kilic, L.Wang-Li, J.-Q. Ni, A.J. Heber, and Z. Li, X. (Under preparation). National Air Emissions Monitoring Study-Southeast Layer Site-Part V: CO2 emission and ventilation. *Transactions of the ASABE*.

Wang, K., Q. -F. Li, C. Xiao, B.W. Bogan, I. Kilic, L. Wang-Li, J.-Q. Ni, and A.J. Heber. (Under preparation). National Air Emissions Monitoring Study-Southeast Layer Site: Part VI-H2S and VOC emission. *Transactions of the ASABE*.

Wang-Li, L., Q.-F. Li, B.W. Bogan, K. Wang, J.-Q. Ni, I. Kilic, A.J. Heber. (Under preparation). National Air Emissions Monitoring Study-Southeast Layer Site: Part III - Ammonia Concentrations and Emissions. *Transactions of the ASABE*.

Wang-Li, Q.-F. Li, K. Wang, B.W. Bogan, J.-Q. Ni, E.L. Cortus, and A.J. Heber. (Under preparation). National air emisison monitoring study-Southeast layer site: Part I-site specifics and monitoring methodology. *Transactions of the ASABE*.

Wathes, C.M., M.R. Holden, R.W. Sneath, R.P. White, and V.R. Phillips. 1997. Concentrations and emission rates of aerial ammonia, nitrous oxide, methane, carbon dioxide, dust and endotoxin in UK broiler and layer houses. *British Poultry Science* 38(1):14-28.

Xin, H., H. Li, R.T. Burns, R.S. Gates, D.G. Overhults, and J.W. Earnest. 2009. Use of CO2 concentration difference or CO2 balance to assess ventilation rate of broiler houses. *Transactions of the ASABE* 52(4): 1353-1361.

Zhu, J., L. Jacobson, D. Schmidt, and R. Nicolai. 2000. Daily variations in odor and gas emissions from animal facilities. *Applied Engineering in Agriculture* 16(2):153-158.